Progress and future prospect of the CRAFFT project for the next generation UHECR observatory

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Abstract. The next generation of ultra-high energy cosmic ray observations will require large detector arrays to achieve large statistics. In order to realize next-generation large-scale detector arrays, the Cosmic Ray Air Fluorescence Fresnel lens Telescope (CRAFFT) project is developing a low-cost simple fluorescence detector (FD). The simple structure of the CRAFFT detector will reduce the cost to about 1/10 of the current FD. We also aim to realize a fully automated observation system. A prototype of the CRAFFT detector has been successfully used to detect cosmic ray air showers. Since the spatial resolution of the simple FD is rougher than that of the current FD, we are developing a new air shower reconstruction method using the waveform fitting method. In this presentation, we report the performance of the CRAFFT detector, detector optimization, and future prospect.

1 Introduction

It is important to clarify the origin of ultra-high energy cosmic rays (UHECRs) above 10^{18} eV for astrophysics. During cosmic rays are propagation, they are diffused in the galactic or extra galactic space due to their electric charge. That make difficult to trace back the origin of the cosmic rays. However, assuming that cosmic rays are light nuclei such as protons, they are expected to travel straight through the galactic or extra-galactic magnetic field at the energy of 10^{20} eV.

The UHECR has been observed by various experiments. Recently, the Telescope Array (TA) experiment reported a "hotspot" in the direction of arrival of cosmic rays above 57 EeV[1]. Pierre Auger Observatory (Auger) reported the existence of a dipole structure in the direction of arrival of cosmic rays above 8 EeV[2]. As described above, various anisotropies in the direction of arrival of cosmic rays have been reported, and such a fact enriches our understanding of the origin of the cosmic rays.

How can we identify the origin of UHECR? First of all, it is necessary to measure the arrival direction distribution with large statistics. Since the flux of UHECR is quit low, a larger scale observation facility than the current one will be required. Since the cost will inevitably increase with a larger scale, a strategy to reduce the cost will be necessary. All-sky observation is also important for the measurement of the arrival direction distribution. Therefore, global deployment of detectors will be necessary. The mass composition measurement is also essential because the propagation mechanism is also an important point.

The TAx4 and AugerPrime experiments are the upgrade of TA and Auger experiments. What should we do as the next step? The concept of Global Cosmic Ray Observatory (GCOS) has been proposed as the next generation UHECR experiment. Candidate detectors for this experiment include the rich SD and Fluorescence detector (FD) developed at AugerPrime, which are reliable. In addition, there are challenging detectors such as POEMA for space-based observations and GRAND for radio observations. The CRAFFT (Cosmic Ray Air Fluorescence Fresnel lens Telescope) or FAST (Fluorescence detector Array of Single-pixel Telescopes) project are also developing simple FDs for the next generation experiment [3].

2 CRAFFT project

The CRAFFT project is developing detectors for the next generation of UHECR observations [4]. In order to clarify the origin of UHECRs, it is necessary to make large-statistics, all-sky observations with a detector that can measure the mass composition. Large-scale observations are inevitable for large-statistics observations, and cost reduction is also an important point. CRAFFT is a research and development project aiming to overcome these problems.

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Table 1. Roadmap of the CRAFFT project

Phase 1	Confirmation of the concept of detectors
Phase 1.5	Optimization of the detector design
Phase 2	Confirmation of the concept of observation
Phase 3	Large scale deployment

The flux of UHECRs is very low, so a larger detection area is required to achieve high statistics. The increase in cost is inevitable for a larger detection area, which could make difficult the realization of next-generation observations. We propose the following strategies to reduce the cost. We can reduce the cost of detector fabrication by simplifying the detector configuration. We can also reduce the maintenance cost by that. Additionally, we want to reduce operating costs by constructing a fully automatic observation system.

From the viewpoint to clarify the origin of UHECRs, it is important to measure the mass composition, which affects the propagation mechanism of cosmic rays, and the distribution of arrival direction in the entire sky. Therefore, detectors are required to be sensitive to the mass composition. FD is one of the most reliable detector in the field, even if surface detector array is also being studied for mass composition analysis. Radio detection using antennas also has a potential in the future. In order to observe the entire sky, it is necessary to deploy detectors both in the northern and southern hemisphere. In order to minimize systematic errors, it is useful to observe the entire sky with the same type detector, and it is also necessary to consider easy transportation of the detector for deployment. Therefore, a simple structure may be more preferred than the detectors now in use.

Another viewpoint is the reduction of damage to the environment, which has become increasingly important in recent years. The larger the detection area, the greater the damage to the environment. Therefore, it is desirable to make the detector density sparsely.

With above considerations, the CRAFFT project is developing an FD with a simple structure. The detector can be a mass composition sensitive by measuring longitudinal development of extensive air showers. The simple structure will allow for low cost and easy transport. The FDs will be installed at intervals of several tens of kilometers, which means that the detector density is sparse. This reduces the number of installation sites and facilitates maintenance. We are currently developing a simple FD according to the roadmap shown in 1. We are currently in the process of moving from phase 1.5 to 2. The development of the simplified FD and the large-scale deployment of 360-degree stations will realize the next generation of UHECR observations.

2.1 Detector

The CRAFFT detector has a simple structure to reduce costs. The original concept is proposed in UHECR 2012 [5]. The main components are a Fresnel lens, a photomultiplier tube (PMT), a UV transmission filter, and electronic circuits such as a FADC and a high-voltage power supply. The Fresnel lens (NTKJ, CF1200-B) is mounted at the aperture and has a size of 1.4 m^2. The transmission of the lens in the UV region is approximately 90%. The lens is supported by two beams to prevent deflection. An 8-inch PMT (Hamamatsu R5912) is mounted at the focal point of the lens. A UV transmission filter (Hoya U330) is placed just in front of the PMT, and the transparency in the UV region is approximately 90%. In the prototype, the UV transmission filter has a spatial filter attached to it, which limits the field of view from $12° \times 12°$ to $8° \times 8°$ degrees. This is to avoid the indefinite sensitivity at the edge of the spherical PMT. Signals are recorded with a 12-bit, 80-MHz FADC (TokushuDensiKairo, Cosmo-Z) through an amplifier. Compared to conventional FDs, this system has fewer channels and is more compact in size, The cost of production can be reduced.

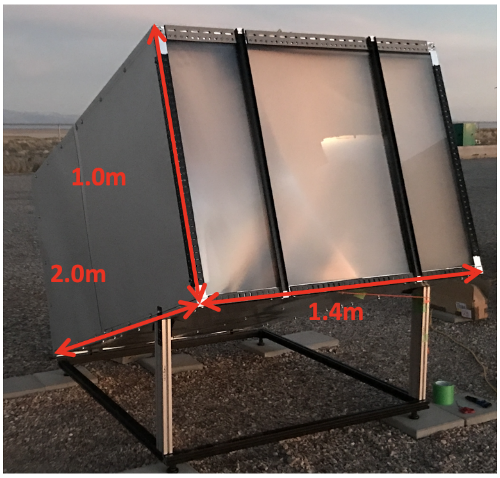

Figure 1. The exterior of CRAFFT prototype detector deployed at TA site in Utah, USA.

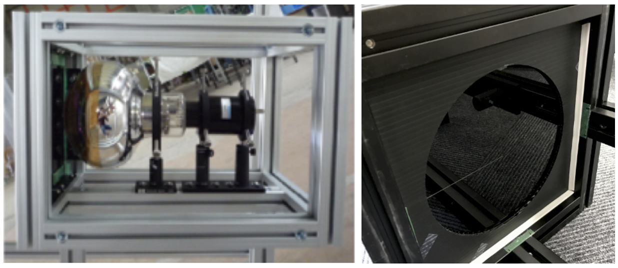

Figure 2. 8 in. PMT with UV transmitting filter. For the prototype, the appeature

The CRAFFT detector is an FD, and it is a sensitive detector for measuring mass composition. The detector is a lens-based telescope, which means that there is no obstruction between the aperture and the focal point, and thus it is characterized by high light collection. The CRAFFT detector consists of an aluminum frame and a galvalume steel plate covering it. All components can be installed inside the detector. A curtain just behind the lens protects the interior during the day time. Because of this packaging, the telescope does not require a building for installation and

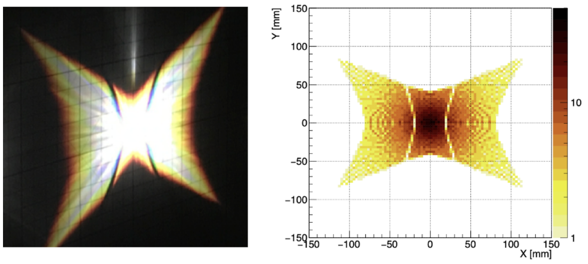

Figure 3. Left: Shape of spot around the focal plane. Right: Reproduced spot shape by raytracing simulation.

can be placed directly on the ground. The detector can be easily transported to multiple experimental sites.

An FD with a Fresnel lens is a unique detector. Therefore, it is necessary to understand the details of the detector performance. The optical performance of the detector was evaluated by ray-tracing simulations. The ray-tracing simulation was performed using ROBAST [6]. Figure 3 shows the actual spot and the shape of the spot obtained by the raytracing simulation, which is well reproduced. The spot size at the focal plane is 44 mm defined in the 95% interval. In the detector simulation, expected waveform has already been simulated, and it is estimated that even a 10^{20} eV cosmic ray air shower can be detected within 30 km with a high signal-to-noise (S/N) ratio.

Test observations were performed using a prototype detector. The four prototypes were installed next to the Black Rock Mesa FD station at the TA experimental site as shown in Fig. 4. The center of the field of view was pointed toward the direction where the Central Laser Facility (CLF) was installed. The elevation angle of three of the detectors was set to 24°–32° and that of the other one to 16°–24°. The test observation took place in November 2017 and observation time was 63.5 hours (10 nights). There were at least 10 obvious air shower events during this observation period. The expected number of events at energies above 10^{17} eV is around 8, which is consistent with the number of events observed. In order to synchronize with TA FD, data acquisition was performed by trigger pulses from TA FD.

Figure 5 and 6 show an example of an actual observed event. This event was also observed by TA FD, and Fig. 6 shows the field of view of the CRAFFT detector superimposed on the TA FD event display for this event. Tracks of the cosmic ray air shower can be seen in the CRAFFT fields of view numbered 2 and 3. Figure 6 is the waveform of this event. Significant signals are seen in detectors 2 and 3 against night sky background. When this event is analyzed by TA FD, the distance from the detector to the air shower is 2.6 km and the energy is $10^{17.7}$ eV. Thus, in the CRAFFT experiment, the establishment of the detector concept of Phase 1 was completed.

2.2 Air shower reconstruction method

As shown in Figure 6, the spatial resolution of CRAFFT is lower than that of conventional telescopes and a shower

Figure 4. Prototype CRAFFT detectors were deployed next to the TA FD building as red circle. The center of field of view is pointed to the CLF.

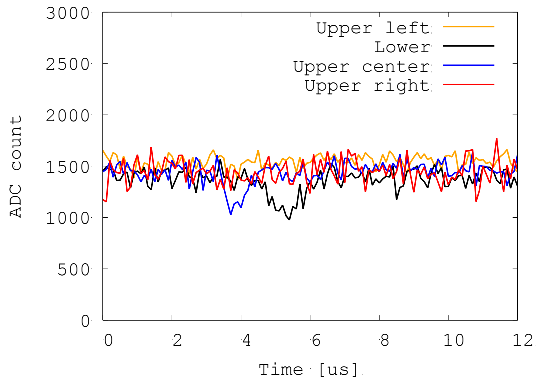

Figure 5. Example of actual waveform observed by CRAFFT detector. Vertical and horizontal axes are FADC count and time slot, respectively.

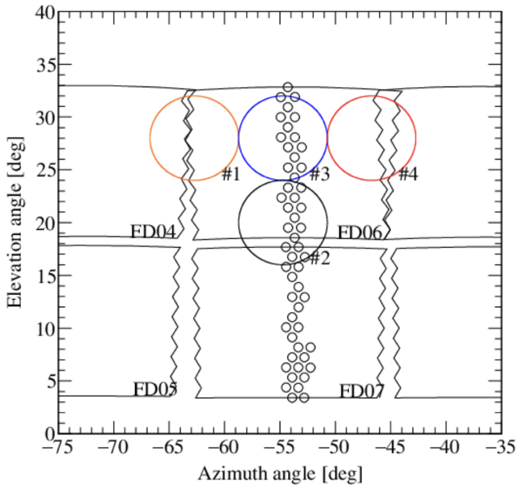

Figure 6. Event display of the air shower event same as Fig. 5 observed by TA FD. Field of view of CRAFFT is superposed. The circle color of CRAFFT field of view correspond to the waveform in Fig. 5

detector plane cannot be obtained. Therefore, we have developed a reconstruction method by waveform fitting. The waveform generated by the simulation as shown in Fig. 7 is compared with the waveform of the real data, and when the simulation agrees with the true value,

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{x_{data,i} - x_{sim,i}}{\sigma_i} \right)^2 \quad (1)$$

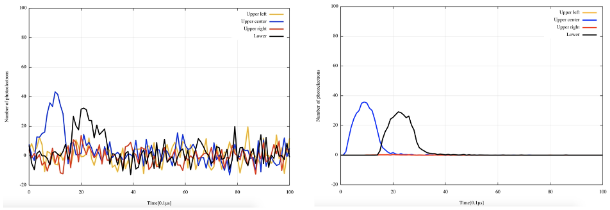

Figure 7. Observed waveform by CRAFFT detector (Left) and simulated waveform (Right) to be compared to observed one.

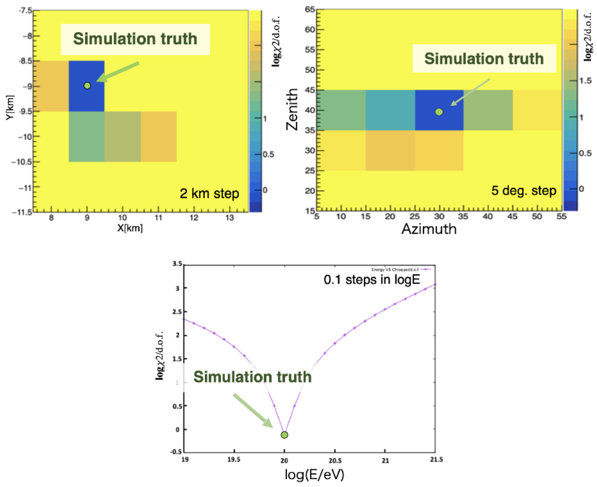

Figure 8. Example of a distribution of χ^2 of a waveform fitting with 5 parameters.

is in principle the minimum. $x_{data,i}$ and $x_{sim,i}$ are waveforms obtained from real data and simulated, respectively, where σ_i is noise due to night sky background, and n is the number of time slots. Figure 8 shows the convergence of χ^2 for a grid search with five parameters. The step of core position, direction and $\log(E/\mathrm{eV})$ are 2 km, 5°, and 0.1 for grid searching of waveform fitting, respectively. This is a monocular analysis under the same conditions as those of the previous test observation. As can be seen, χ^2 converges around the true value. However, X_{max} is fixed here. In a Monte Carlo study at 10^{20} eV, the accuracy of geometry determination by four-parameter fitting is estimated to be about ±3 degree in the direction of arrival and ±200 m m in the core position in the monocular analysis. Currently, we are developing a procedure for analysis based on six-parameters fitting by adding X_{max} and energy. The six-parameters fitting however requires a more efficient algorithm for reaching the convergence. Stereo and triplet observations will be very effective in constraining the parameters.

3 Detector optimization and future plan

3.1 Optimization of detector configuration

Since we have successfully detected cosmic rays with the CRAFFT prototype, we are trying to optimize the configuration while maintaining the cost reduction[7]. One guideline for optimization is to increase the field of view per detector, from the viewpoint of cost reduction. To increase the field of view per telescope, the detection area of the light detection area composed by PMTs at the focal point should be increased. This is easier than with conventional FDs, since a refracting telescope does not screen the incident light even if the focal plane is enlarged. Another guideline is to improve the accuracy and S/N ratio of the reconstruction. To improve the accuracy of reconstruction and S/N ratio, the field of view per channel should be narrower. From this point of view, we performed Monte Carlo studies on various configurations of the PMT size and arrangement, and the light guide used to guide the light incident in the gap to the PMT, to estimate the most appropriate arrangement of the PMT. As shown in Fig 9, a four by four array of 5-inch PMTs seems to be a good configuration. For this configuration, the accuracy of geometry determination by four-parameter fitting was estimated to be 2.3° in the arrival direction and 160 km in the core position. The field of view per PMT is about 6.5° , and the total field of view of the telescope is about 26°. The new configuration of the CRAFFT detector can cover the field of view of 2.6 TA FDs.

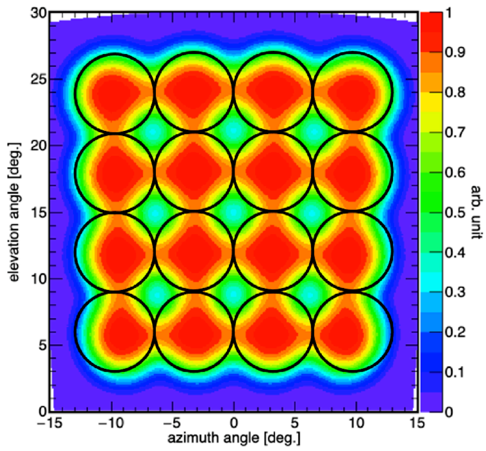

Figure 9. Sensitivity map as a function of arrival direction of incident light at the focal plane with 16 PMTs with 5 in. diameter. The arrangement of PMTs of new configuration is four by four matrix.

3.2 Preparation for the confirmation of observation concept

Based on the optimized new configuration of the detector, each new component should be evaluated. The PMT selected is the Hamamatsu R877-100. The diameter of the incident window of this PMT is 5 inches, the surface is flat, and the material of photocathode is super bialkali. Because of the large incident window of the PMT, two-dimensional non-uniformity of sensitivity is important. We have developed a system to measure a two-dimensional non-uniformity of PMT gain consisting a UV LED and an XY state, and we are measuring the sensitiv-

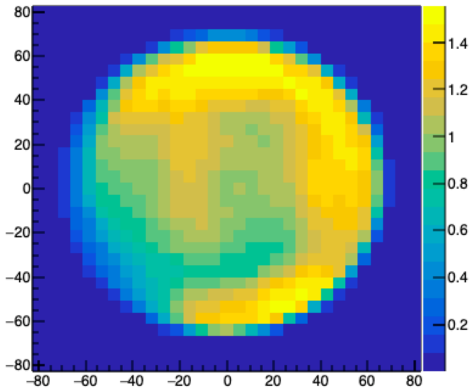

Figure 10. Example of a measurement of non-uniformity of PMT gain to be used for new configuration.

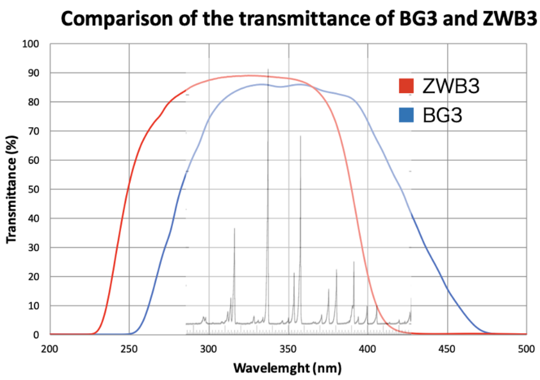

Figure 11. Transmittance of UV transmitting filter. ZWB3 is planed to be used for CRAFFT and BG3 is used for TA FD. Fluorescence spectrum is superposed.

ity of incident window of all the PMTs to be used for the test observations scheduled for next summer. The upper of Fig. 10 is an example of the measured sensitivity relative to the center. These results should be used for simulation and shower reconstruction.

ZWB3 (Haian Subei Optical Glass Factory) will be used as the UV transmission filter. Figure 11 shows the measured transmittance at each wavelength of ZWB3 and BG3 used for FD in the TA experiment and the fluorescence spectra are overlaid . The transmittance of ZWB3 is about 90% at the main peaks of fluorescence, which is sufficient.

In cost reduction, not only production costs but also operating costs must be considered. To reduce operating costs, it is important to have maintenance-free and automatic observations. We have conducted long-term tests for automatic observation. The automatic observation system consists of an environmental monitor and a control unit shown in Fig. 12. The environmental monitor measures the weather conditions such as wind speed, humidity and rainfall, and brightness, and determines whether the observation is possible or not before starting the data acquisition. Figure 12 shows examples of monitors for humidity, illumination, rainfall, wind speed and so on. Cloud mon-

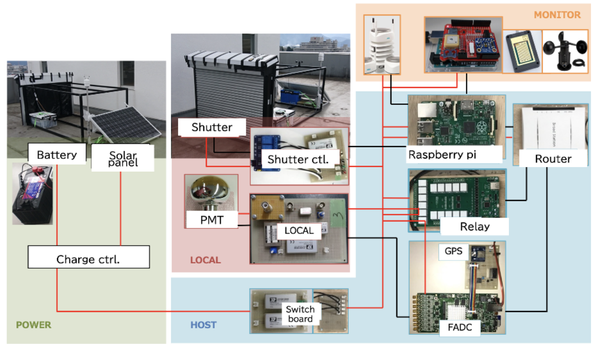

Figure 12. Block diagram of the automation system of CRAFFT for long-term tests at Shinshu University.

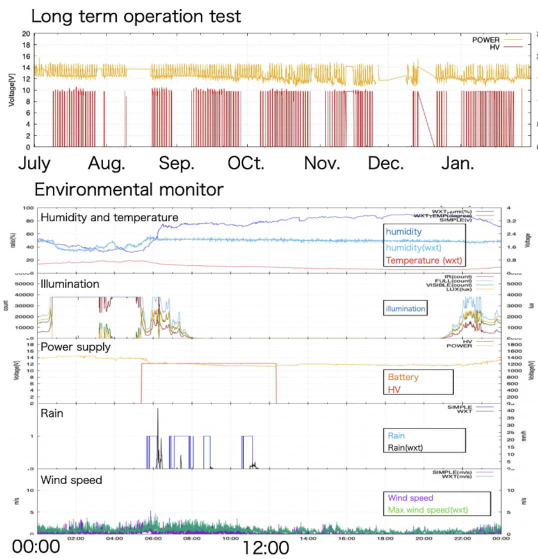

Figure 13. Example of the monitor plot of the automation system in long-term tests.

itors using CCD monitors are also useful [8]. When it is determined that the observation is feasible, a high-voltage power supply is automatically applied before the start of the observation, and the electric shutter is opened, then the data taking is started.

Long-term tests were conducted to demonstrate the robustness of the automation system. Detectors for cosmic ray observations, such as CRAFFT, are supposed to operate without a commercial power supply. Therefore, all the power for these systems is provided by a solar power system. The site is the rooftop of the Nagano campus of Shinshu University. Figure 13 shows the results of the seven-month test. This figure shows that the power supply system was stable and the high-voltage power is applied during the observable hours on the days when it is determined that the system is observable. We are planning to conduct test observations using such a system to establish the observation concept as phase 2.

Test observation at TA BR site to confirm the observation concept by simple FDs is planed. We will use four telescope which can cover the field of view of one TA FD station approximately. In this test, we want to realize stable observation with automation system.

4 Summary

Various experiments have observed UHECRs and it is expected to clarify their origin. Large-scale experiments with large statistics and sensitivity to the mass composition will be required, and large scale experiments cannot be avoided that will make the cost high. The CRAFFT project aims to develop a simple FD to realize the next generation of UHECR observations with the strategy of cost-reduced FD. We have demonstrated the principle of the simple FD using a Fresnel lens through test observations. We are now planning to establish the concept of stereo or triplet observations. In the future, we would like to install the simple FD globally to realize all-sky observation. Since simple SDs are easy to transport, simple FDs can be distributed to any location. Simple FD stations with $\sim 20\,\mathrm{km}$ spacing are to be set up to provide a global view of the entire perimeter. If the total area of $400,000\,\mathrm{km}^2$ is realized, sufficient statistics will be obtained even considering the FD duty cycle of about 15%. The development of such simple FD can be a powerful strategy for future projects such as GCOS.

Acknowledgements

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