

# Detection of ultra-high energy cosmic ray air showers by Cosmic Ray Air Fluorescence Fresnel lens Telescope for next generation

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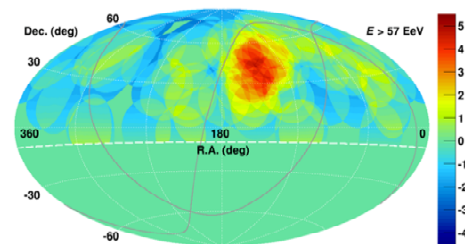
**Abstract.** In the future, ultra-high energy cosmic ray (UHECR) observatory will be expanded due to the small flux. Then, cost reduction is useful strategy to realize a huge scale observatory. For this purpose, we are developing a simple structure cosmic ray detector named as Cosmic Ray Air Fluorescence Fresnel-lens Telescope (CRAFFT). We deployed CRAFFT detectors at the Telescope Array site and performed a test observation. We have successfully observed UHECR air showers. We will report the status and the result of the test observation.

## 1 Introduction

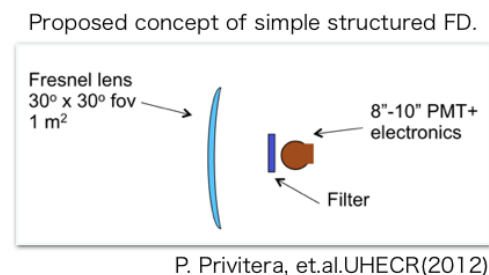
Since the discovery of cosmic rays by V.F. Hess in 1912, cosmic rays in the wide range of energies are observed by various experiments. However, it has been difficult to identify the sources of cosmic rays so far, because almost all cosmic ray are charged particles deflected by the galactic or extra-galactic magnetic field. On the other hand, it is also predicted that ultra-high energy cosmic rays can propagate straight in such magnetic field. Telescope Array (TA) reported that there is a hotspot in the arrival direction of ultra-high energy cosmic rays above 57 EeV [1]. It is expected that the source of ultra-high energy cosmic rays can be identified with more statistics. However, if the composition of ultra-high energy cosmic rays is dominated by heavy nuclei, the deflection cannot be ignored. The High Resolution Fly's Eye reported that the composition of cosmic rays above 1.6 EeV is dominated by protons [3] by  $X_{\max}$  measurements. TA composition is also consistent with light, largely protonic, composition [4]. On the other hand, Pierre Auger Observatory (Auger) has indicated transition of the composition, from a light to heavy component at energies above  $10^{18.3}$  eV [5]. However, TA and Auger  $X_{\max}$  data are in good agreement within the systematic uncertainties at the moment [6]. In order to clarify the sources of ultra-high energy cosmic rays, we have to understand the 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 a mass composition sensitive detector such as a fluorescence detector until we conclude the mass composition. For this purpose, a low cost fluorescence detector (FD) was proposed [2]. The low cost FD

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**Figure 1.** Hotspot in the arrival direction of UHECRs reported by TA. [1]



**Figure 2.** The concept of a simple structure Fresnel lens telescope for UHECR detection.

is a very simple structure consisting of a Fresnel lens, UV transmitting filter and a large photomultiplier tube (PMT) as shown in Fig. 2. Based on this concept, we are developing a Fresnel lens FD. The FAST project is also developing a low cost FD consisting of mirrors and PMTs [9]. As other strategy for ultra-high energy cosmic ray observation, fluorescence detector from space are also under development [10][11][12].

## 2 CRAFFT detector

The Cosmic Ray Fluorescence Fresnel lens Telescope (CRAFFT) is a simple structure fluorescence detector (FD). CRAFFT detector mainly consists of a Fresnel lens, and UV transmitting filter and an eight inch PMT. The details of components and costs are listed in the table 1. For the cost reduction, the structure of CRAFFT is very simple and use less components than a typical FD [7][8].

Figure 3 is the exterior of the CRAFFT detector deployed at the TA FD site. The structure of the CRAFFT detector is made of black anodized T-slotted aluminum extrusions. At the aperture, a Fresnel lens is supported by two aluminum frame to keep flatness. The detector is covered by 0.4 mm thick steel plate so that CRAFFT doesn't need buildings to contain detectors. It is so easy to deploy that CRAFFT detectors can be deployed on the ground directly.

The focal length, dimensions, and pitch of the Fresnel lens are width of 1400 mm, length of 1050 mm, thickness of 3 mm and 0.33 mm, respectively. The material of the Fresnel lens is acrylic plastic (Mitsubishi Chemical, ACRYLITE 000). Just behind the lens, there is a roll curtain to prevent the incident light in day time.

At the focus, a PMT is mounted as shown in Fig. 4 with a UV transmitting filter to reduce the night sky background in the visible range. We use an 8-inch large photocathode area PMT with a D type socket of a DC coupling with a negative high voltage power supply. The spectral response and the peak wavelength of the PMT are from 300 nm to 650 nm and 420 nm. The quantum efficiency at 390 nm and the typical gain with 1500 V of the PMT are 25% and  $1.0 \times 10^7$ , respectively. The field of view (F.O.V.) is designed as  $\pm 6^\circ$ . In front of the UV transmitting filter, for the test observation, a spacial filter of 16 cm diameter is attached to limit the F.O.V. to  $\pm 4^\circ$  to reduce the effect of the periphery of the PMT with a spherical photon entrance window.

The signal from the PMT is digitized and recorded by the FADC board on which Linux is available with Zynq. Zynq is a FPGA on which we can implement our own trigger algorithm we are now developing. The sampling rate and resolution of the FADC are 80 MHz and 12 bits, respectively. We can time events with precise time stamps by a GPS module (Linx Technologies Inc. EVM-GPS-FM), which provides 1 pulse per second as well as time information.

Most of the FDs used now are mirror type telescopes. In the case of mirror type FD, PMT clusters are an obstacle to prevent incident light, because incident light come from behind the PMT clusters and size of PMT cluster at the focal plane is large. On the other hand, in the case of lens type FD, there is no obstacle between lens and focal plane. Because of this, the efficiency of light collection of lens type FD is better than that of mirror type FD, when the size of apertures are the same.

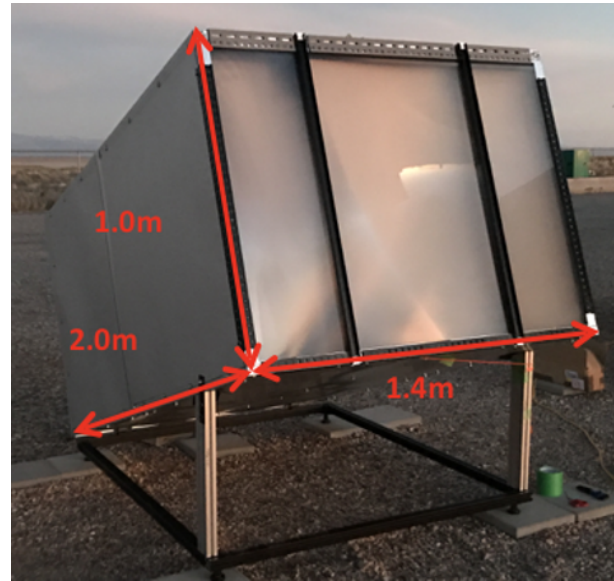


Figure 3. CRAFFT detector deployed at TA site.

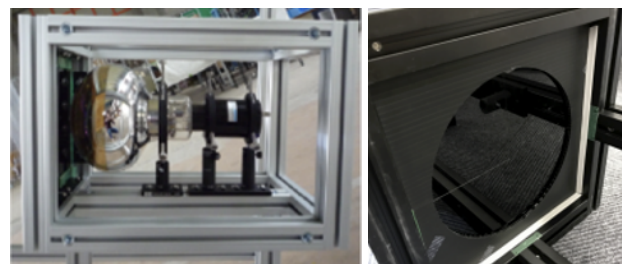


Figure 4. Left: PMT mount. Right: Spacial filter to limit the light with large angles [15].

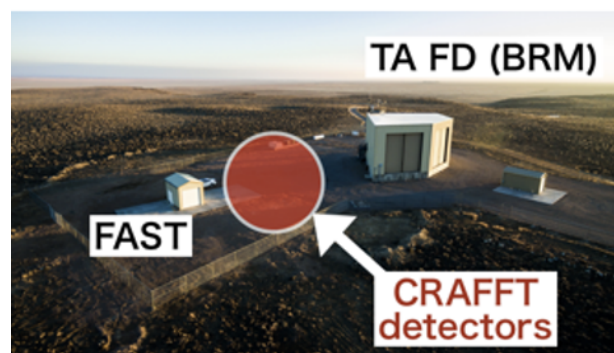
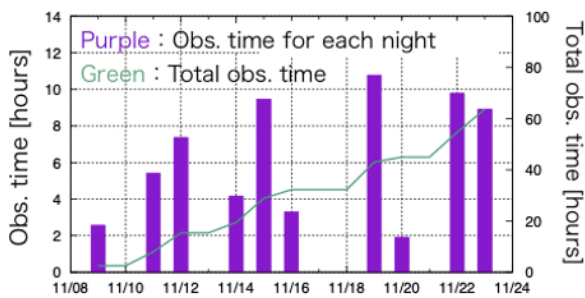


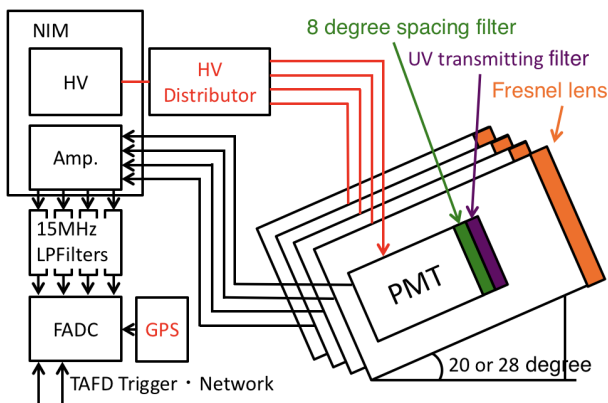
Figure 5. Upper: Four CRAFFT detectors deployed at TA FD Black Rock Mesa (BRM) site. Lower: The location of CRAFFT detectors. CRAFFT detectors are arranged between TA FD station and the hut of FAST experiment [15].

### 3 Test observation

In 2017, we deployed four CRAFFT detector at TA FD site as shown in Fig. 5. The F.O.V. of CRAFFT compared with those of TA FDs are shown in Fig. 15. The elevation angle of upper and lower viewing detectors are  $28^\circ$  and  $20^\circ$ , respectively. We performed a test observation for ten nights from November 9 to November 23, when the TA FD was operating. The total observation time is 63.4 hours (Fig. 6). Figure 7 is the block diagram of data acquisition (DAQ) system. For this test observation, trigger pulse is provided from TA FD to record waveform as a sure method to acquire the signal of air showers. The total number of recorded events are 556,255 by the TA FD triggering pulse.



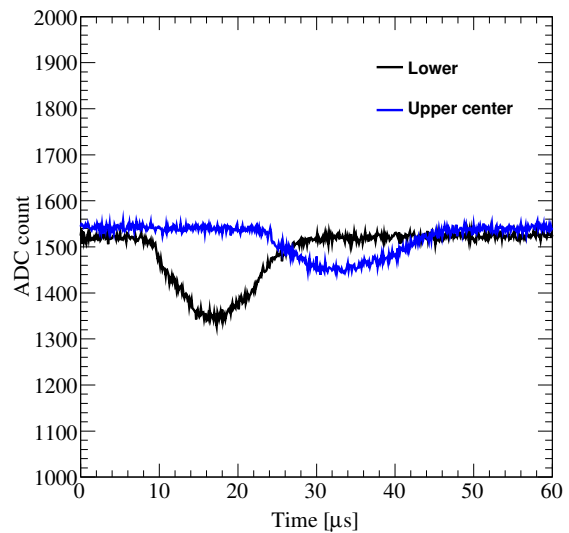
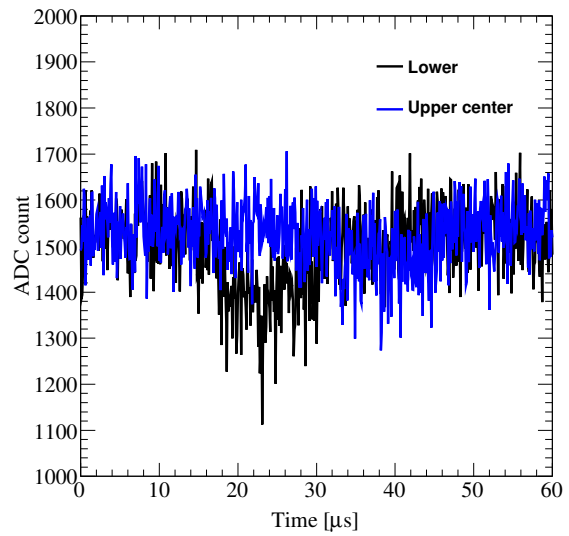
**Figure 6.** Purple is the observation time of each night and green is the total observation time.



**Figure 7.** The block diagram of data acquisition system of CRAFFT detector for the Test observation in 2017.

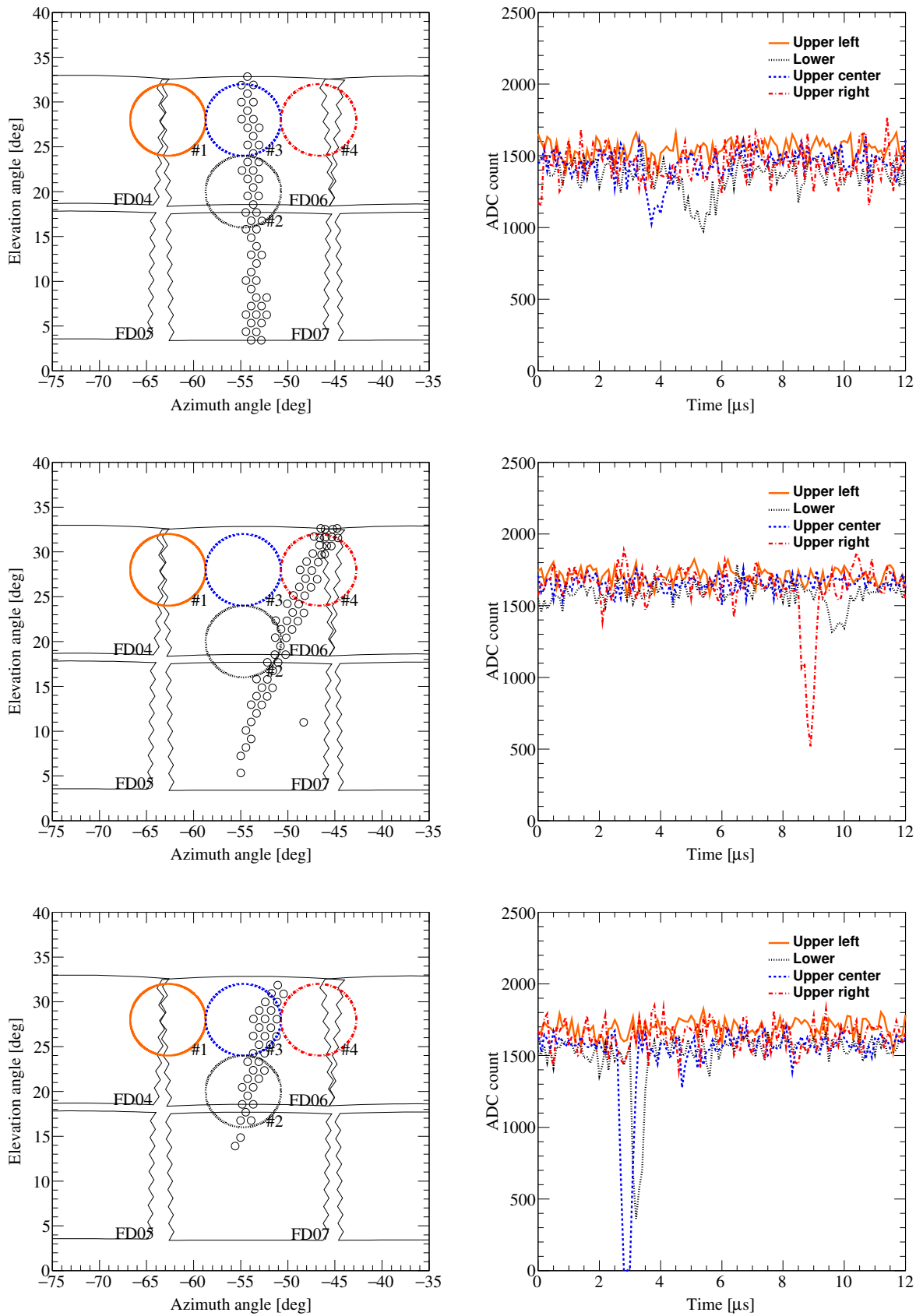
As a performance test, we search the signal of the laser event of the Central Laser Facility (CLF). CLF is located 20 km apart from CRAFFT detectors. CLF uses a Nd:YAG pulse laser, wavelength of which is 355 nm. Typical energy of the laser is 5 mJ. The number of photons of CLF detected at TA FD BRM site corresponds to  $10^{20}$  eV air showers. We can easily identify the CLF events by the time stamp. Upper of Fig. 8 is a waveform of CLF detected by CRAFFT detector and lower of Fig. 8 is the averaged waveform over 133 events.

We searched air shower event candidates from all of the recorded events. Most of the data doesn't include signal, because we recorded waveforms by TA FD triggering



**Figure 8.** The waveform of CLF events. Upper: Single event. Lower: Averaged over 133 shots. Blue is center of upper viewing detector and black is lower viewing detector [15].

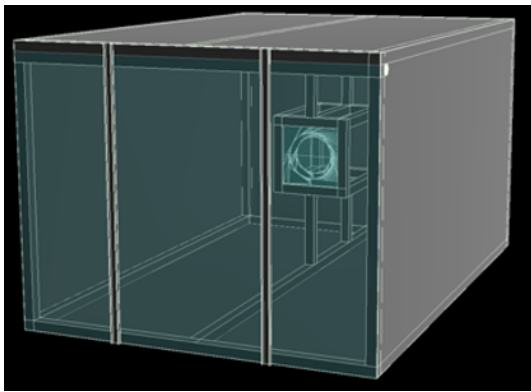
pulse and our F.O.V. is smaller than TA FD as shown in Fig. 15. We select the significant signals against the night sky background, and removed the CLF event using time stamp. Moreover, we removed the signals with large pulse width such as artificial light (ex. air plane). There are 6,600 events which are in coincidence with two or more CRAFFT detectors. Finally, we could select ten apparent air shower events by eye scanning. Example of air shower events detected by CRAFFT detector are shown in Fig. 9. The expected number of air shower with the energies above  $10^{17}$  eV is roughly estimated as  $\sim 8$  events per month.



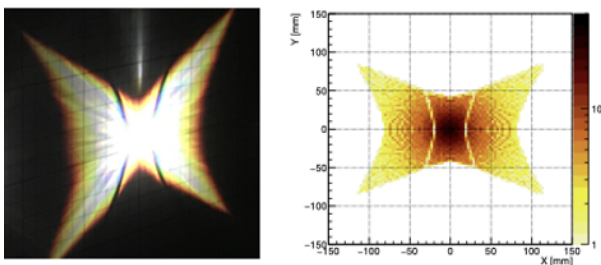
**Figure 9.** Typical air shower event acquired by CRAFFT. Left: The FADC count of each channel that can be compared within the accuracy of 20%. Right: TA FD event display. Solid line is the edge of TA FD F.O.V. 1° circles are views of TA FD triggered channels. 8° circles are the F.O.V. of CRAFFT.

## 4 Ray tracing simulation

We also developed detector simulation to understand our optics, to optimize the configuration of the detector, and develop the analysis method. The actual detector configuration of CRAFFT is considered in the ray tracing simulation as shown in Fig. 10 using ROBAST [13]. Left of Fig. 11 is the actual spot and right is simulated spot. This unique shape of spot is caused by the shape of squared Fresnel lens. We can see the shade of lens support aluminum frames is reproduced correctly. The shape of spot looks unique and complex but the effect of the tail is not serious. The 95% spot size at the focal plane is 44 mm which is smaller than the tail of the spot as shown in Fig. 12. Here, considered wavelength is from 280 ~ 400 nm. We also estimated the direction dependence of light collection efficiency as shown in Fig. 13. We have to consider this dependence to estimate detection efficiency, because we use only single PMT of 8 inch which covering wide F.O.V.



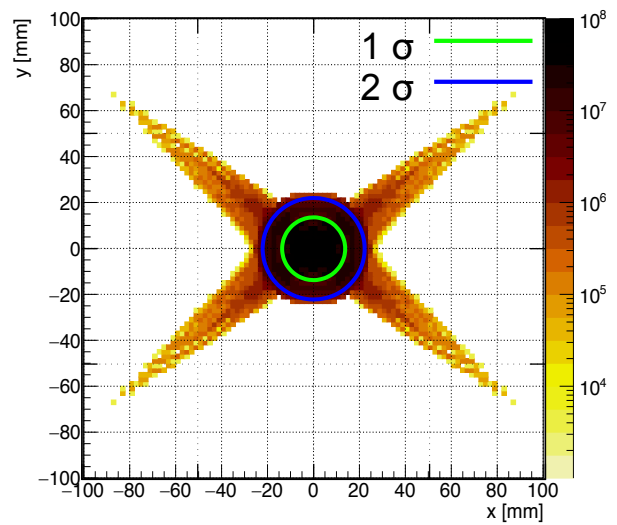
**Figure 10.** Reproduced CRAFFT detector configuration in the ray tracing simulation.



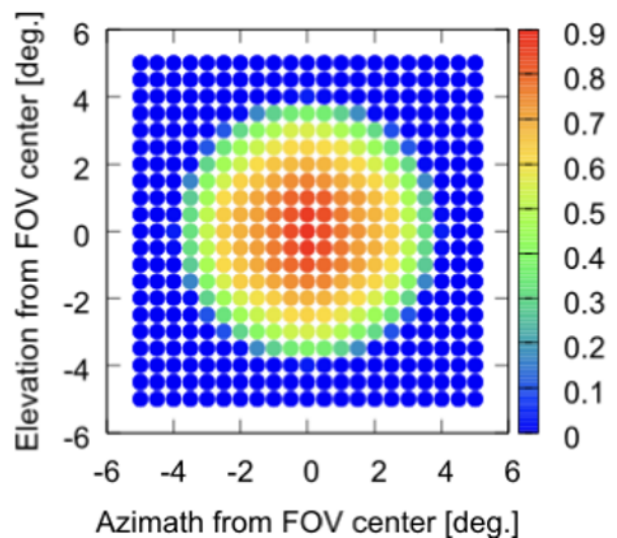
**Figure 11.** Left: The unique shape of spot of CRAFFT detector. Right: Simulated spot shape. The shade of the lens support can be seen in the simulated spot and actual spot.

## 5 Automation system

CRAFFT detectors will be arranged as a huge array for ultra-high energy cosmic rays observation, so that it will be difficult to access frequently. Because of this, CRAFFT should be operated by full automation system and maintenance free. Now we are testing the solar power system



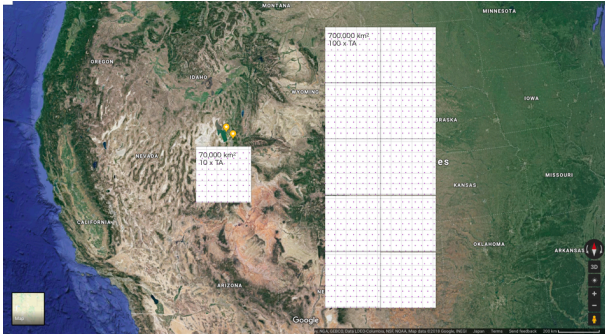
**Figure 12.** Simulated spot at the focal plane. Green and blue circles are defined as a spot size with 95% and 68% photons inside.



**Figure 13.** The light collection efficiency at the focal plane for each incident directions.

and automation DAQ system. We also update electronics for slow control in order to switch from a commercial product to original electronics developed by our own for cost reduction. All of the procedure such as initialization of electronics, weather monitor, DAQ and shutdown will be done, automatically.

Protection and fail-safe system is also important. Now, for the protection of the detector from daylight we installed a roll curtain which is manually operated just behind the Fresnel lens. We will update the protection system using electric powered shutter which will be mounted in front of the Fresnel lens. We are planning the automation system test in 2018 Oct. at TA FD site.



**Figure 14.** Idea of Huge array for ultra-high energy cosmic ray observation using CRAFFT detector. Map data ©2018 Google

## 6 Future prospect

We proved the detection ability of ultra-high energy cosmic ray air showers by CRAFFT detector. We propose a huge CRAFFT array for the next generation of cosmic ray observatory as shown in Fig. 14 Overlaid on the U.S. map. In order to clarify the origin of ultra-high energy cosmic ray, we need more detection area than ever. The detection area of TA is  $\sim 700 \text{ km}^2$ . If we need 100 times more than TA, the detection area should be  $70,000 \text{ km}^2$  which is shown in Fig. 14 as a left side square area. However, the duty cycle of FD is 10% of surface detector array. If we realize 100 times TA using only FDs such as CRAFFT, we need  $700,000 \text{ km}^2$ . which is shown in Fig. 14 as a right side square area. If it is difficult to prepare such huge area at the same place as shown in Fig. 14, divided array can be distributed in any place, because the important things is total area.

If the target energy is above  $10^{20} \text{ eV}$ , CRAFFT can detect air showers within  $\sim 25 \text{ km}$  [14]. When we arrange the CRAFFT stations at intervals of  $25 \text{ km}$  over  $700,000 \text{ km}^2$ , we need 900 CRAFFT stations. One CRAFFT station consists of 30 telescopes. Here, the F.O.V. of each telescope is assumed as  $12^\circ$ . Under these assumption, total cost will be roughly  $\$250,000,000$ .

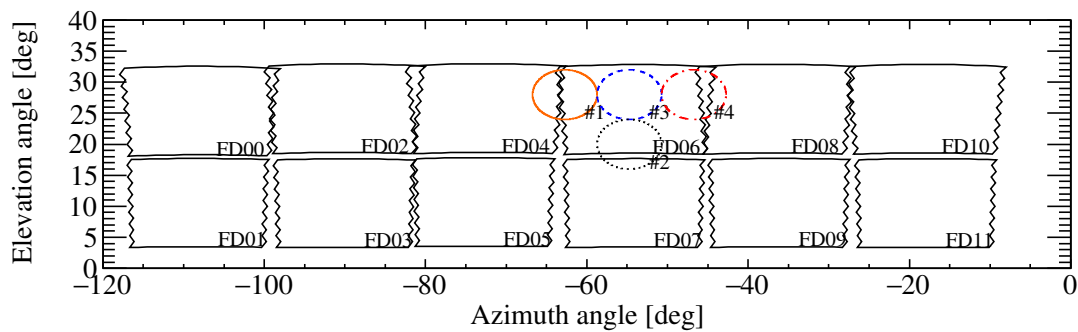
## 7 Summary

We are developing a simple structure low cost fluorescence detector for the next generation ultra-high energy cosmic ray observation named as Cosmic Ray Air Fluorescence Fresnel lens Telescope (CRAFFT). We deployed four CRAFFT detectors at TA FD site, and performed test observation from 2017 Nov. 9 to Nov. 23. In this period, we operated CRAFFT in ten nights, and total observation

time is 63.5 hours. We finally succeeded to detect 10 ultra-high energy cosmic ray air shower events. we proved our detector can be used for the next generation cosmic ray observatory.

## Acknowledgment

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**Figure 15.** The F.O.V. of each CRAFFT detector is shown as circle drawn over the F.O.V. of the TA FDs edge of which is shown as a solid line [15].

**Table 1.** The list of the components of CRAFFT detector and each cost.

Component	Product	Specification	Cost/FD
Structure	MIWA	Anodized, Alminum frame	950
Fresnel lens	NTKJ, CF1200-B	1.4 m <sup>2</sup> , f=1.2 m	370
UV trans. filter	Hoya, UL330	~80%, 300-360 nm	3,00
PMT	Hamamatsu, R5921	8 inch	2,000
FADC	TokushuDenshiKairo, Cosmo-Z	80 MHz, 12 bit	290
Amplifier	Lecroy, 612AM		1,000
HV	CAEN, N1470R	8 kV, 3 mA	1,600
		Total (\$):	9,210

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