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Geometry calibration of Fluorescence Detector using standard light source mounted on UAV

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We have developed a standard UV-LED light source mounted on an unmanned aerial vehicle (UAV), so-called the *Opt-copter*, for the calibration of the Fluorescence Detectors (FDs) of the Telescope Array experiment. The positioning accuracy of the GPS controlled UAV is $\sim$ 10 cm, which allows accurate calibration of the pointing directions of the FD PMTs. We tried the analysis of the field of view of the telescope using this system. The pointing direction was determined to be less than 0.1 $^\circ$ using our analysis. We report the hardware details of the device and the status of data analysis.

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1. Introduction

The Telescope Array (TA) experiment, located in Utah, USA, aims to observe ultra-high energy cosmic rays (UHECR) at energies above 10^{18} eV. The TA uses two types of detector: the Fluorescence Detector (FD) that measures photons emitted from air molecules along a cosmic ray, and the Surface Detector (SD) that measures shower particles on the ground. The TA detector has been in operation since May 2018 [1][2].

This report deals with the calibration systems for the TA FDs. The accuracy of the optics and PMT gain is important in determining cosmic ray parameters such as arrival direction and energy. One common method for calibrating the pointing direction of a light sensor is to use a light source whose position is known exactly like a star. We have developed the FD calibration system with a positioning accuracy of $\sim$ 10 cm, using high intensity UV LEDs mounted on a GPS controlled Unmanned Aerial Vehicle (UAV)[**?**]. Its position stability and portability allow to adjust the FD's optical system with excellent pointing accuracy with a single standard light source for all the FDs in 3 locations each 35 km apart. A conceptual diagram of this device (*Opt-copter*) is shown in the Fig. 1.

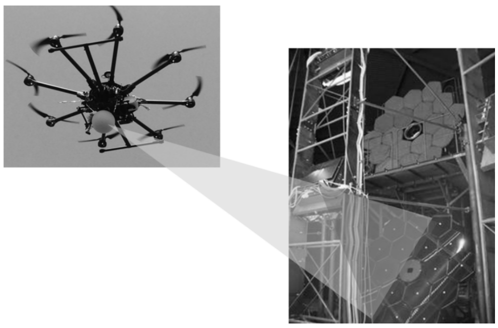

Figure 1: The conceptual diagram of measurement by Opt-copter.

Figure 2: The appearance of the Opt-copter that has eight arms, all of which are able to be folded. A GPS antenna is mounted on the top of this device.

2. The Opt-copter

The Opt-copter consists of an unmanned aerial vehicle (UAV), a UV-LED as the light source, and several GPS modules (Fig. 2). The Opt-copter position accuracy enables calibration of FD PMTs with the accuracy of 0.1 degrees or better.

2.1 UAV

We use a high-stability 8-rotor helicopter (DJI *S1000+*) to load the light source. The size of the UAV is $400 \times 400 \times 500$ mm^3 (WxDxH) when the arms are collapsed, and its portability with automatic leg and centrifugal propeller folding mechanism helps works in wilderness at night.

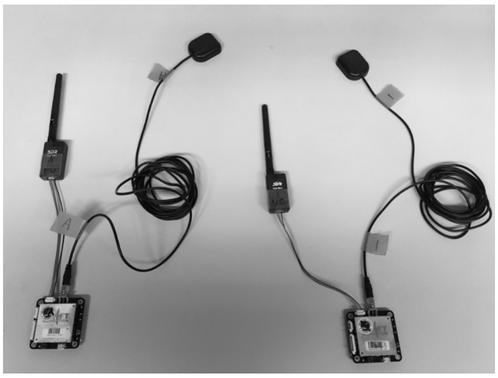

Figure 3: The Piksi is composed of two modules and records the relative position of them.

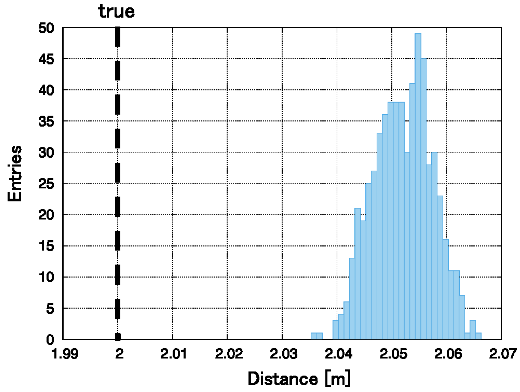

Figure 4: Ranging accuracy of RTK-GPS on the ground.

This UAV allows both manual control and programmed flight path control. A high-power and high-efficiency heat radiation motor and the all-carbon body frame of the vehicle realize 12 $\sim$ 15 fights, with a 16000 mAh lithium polymer battery. This *S1000+* is also designed to load a camera for aerial photography, and we use this room ($\sim$ 30 cm^3) to mount the light source and electronic devices. The maximum load weight is 7 kg. The flight controller (DJI *A3*) consists of a GPS and an attitude sensor to measure acceleration and atmospheric pressure. The positioning accuracy of *S1000+* with *A3* is about 3 m. The opt-copter is designed to hover 300 m ahead of the FDs in calibration flights. The positioning accuracy of 3 m corresponds to a pointing accuracy of 0.6° at the distance of 300 m (c.f. the field of view of each PMT is 1°).

2.2 RTK-GPS

Because there is a systematic error of 0.6° in UAV flight control system, Opt-copter is equipped with RTK-GPS module for high precision positioning. For a PMT pointing calibration with the accuracy of 0.1°, a positioning accurary of 0.5 m is needed, and the Real Time Kinetic GPS (RTK-GPS) system (Swift Navigation, *Piksi*) enables this (Fig. 3). RTK-GPS consists of two GPS modules, and records the relative position of the GPS antennas using the phase difference of the signals emitted from the GPS satellites. The position accuracy of RTK-GPS is typically 10 cm after GPS calibration more than 1.5 hours. We evaluated the positioning accuracy on the ground. The RTK-GPS is tested the movement distance where was measured to 2 m from the original point, and this measurement test that is 10 times trial. The RTK-GPS was tested for horizontally (East - West, North - South) and vartically, and the test of the above procedure for all of dirction tests was performed 10 times. The distribution of the measured relative distances between the two modules is shown in Fig. 4, which exibits that the horizontal and vertical accuracy of RTK-GPS is better than 10 cm. By loading one GPS module of RTK-GPS on the UAV and placing the other at a reference point on the ground where the position is previously measured in good accuracy, it is possible to know actual positions (the accuracy is better than 0.05°) of the UAV and the direction seen from the FDs.

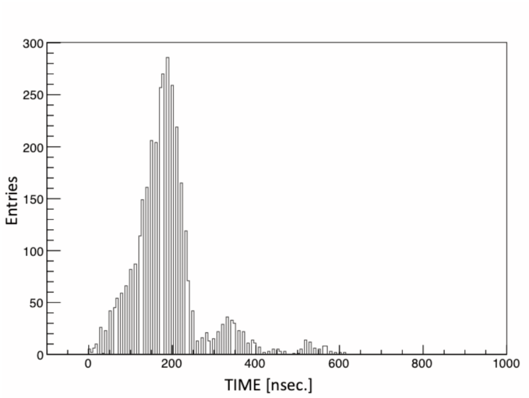

Figure 5: Time difference between pulse generator for light source and RTK-GPS measurment for ranging.

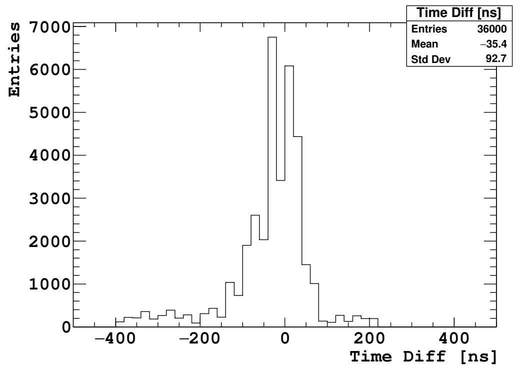

Figure 6: Time difference between the GPS-based pulse generators for FD trigger and the GPS-based pulse generator for the light source.

2.3 The triggering system

The TA FD consists of a composite light collecting mirror of 3.3 m diameter and a 16×16 cluster of PMTs (the *camera*) as shown in Fig. 1. The FD is designed to trigger the data acquisition system when photons are detected with more than 5 adjoining PMTs within $25.6\,\mu$s to detect cosmic ray showers, or by an external signal to the FD. Since the size of the Opt-copter light source image on the FD camera is as small as the size of a PMT, which was confirmed by our preparatory measurement hovering the UAV at the center of the field of view of an FD, the self-triggering of FD does not work for Opt-copter signals. Therefore we need a trigger generator for this to send trigger pulses both to FD and the light source in order that a measurement of the light source position, a UV-LED flash, and the FD data acquisition are made at the same time. The Opt-copter on flight position measures by the RTK-GPS as at the frequency of 10Hz, and we use two GPS-based pulse generator of 10Hz: one on the Opt-copter for LED flashes, and the other is to trigger the FD data acquisition. This frequency is well below the maximum trigger rate of the TA FD, 30 Hz. All the three GPS modules are presumably synchronized by the GPS-PPS signal every second. We compared the signal timing differences using an external high precision pulse generator that is also synchronized with GPS-PPS, and the GPS pulse for the Opt-copter as shown in Fig. 5. The distribution of the time differences between the two GPS-based pulse generators for the Opt-copter and for the FD trigger is presented in Fig. 6. This shows that the synchronization of the GPS-based pulse generator is as good as $0.1\,\mu$s, which is much smaller than the width of the UV-LED flash that is $10\,\mu$s.

2.4 UV-LED light source

The optical system of the TA FD is optimzed for photons of wavelengths between 300 and 400 nm, for fluorescence light from nitrogen and oxgen molecules. We use 12 UV-LEDs (Roithner Lasertechnik, H2A1-H375-E) at wavelength of 375 nm. The emission pattern of each LED is highly anisotropic, and we use a spherical light diffuser to minimize the UAV attitude dependence

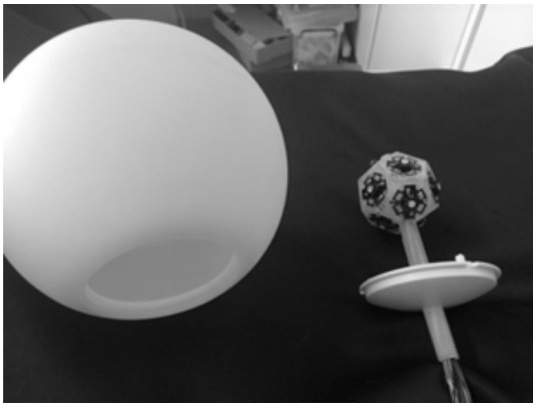

Figure 7: The light source mounted on the Opt-copter is consisted of 12 UV-LEDs attached on dodecahedron and a spherical diffuser.

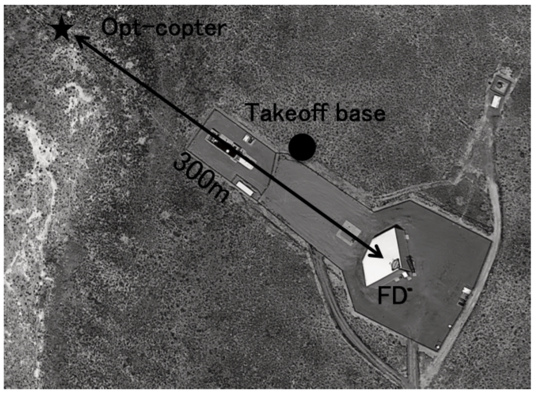

Figure 8: A bird's-eye view of the FD site taken by the flight.

of light intensity seen from the FDs. The diffuse is dodecahedron in shape by 3D printer made of acrylic resin, and the LEDs are attached on every side of the diffuser (Fig. 7).

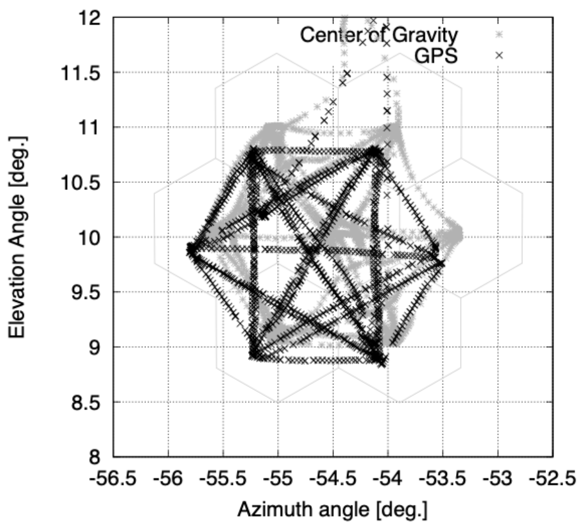

Figure 9: Measurement by RTK-GPS on FD viewing field (Gray points) and center of gravity of detected light by FD (Light gray lines).

3. Operation and data

The position of the launching point of the Opt-copter ahead of each FD station is measured with good accuracy in advance. The light source is designed to be seen from the FD at the distance of 300 m, and the vehicle flies around in the field of view of the camera with a positioning accuracy of 10 cm, which corresponds to a directional accuracy of 0.02°. Figure 8 shows a bird's eye view of the FD site by an Opt-copter flight.

The position information obtained by the Opt-copter is obtained from the FD and the RTK-GPS. The center of gravity of the amount of received light by PMTs of FD indicates the position of the light source, and the RTK-GPS measures the relative position of the GPS antenna on the Opt-copter and the GPS antenna on the ground reference station. The ground reference station is a monument that has already been positioned by mthe measurement by another GPS module with high accuracy. To compare the two, we project the information by the RTK-GPS on the FD view (See Fig. 9.). The trajectories of the detected the center of gravity of received light by the FD appear to be biased to the center of each PMT, which is different from the position of the projected image by the RTK-GPS measurement. If the image of the light source is sufficiently smaller than the size of one pixel of the FDs (PMT), the center of gravity is biased towards the center of the PMT, which contains the main part of the image of the light source. By measuring the center-of-gravity shift when the measurement by the RTK-GPS is taken as the true position, it is expected that the optical characteristics of the FD can be obtained. We evaluate the correlation of the opening angles between the RTK-GPS and the center of gravity from the view center of the FD. Figure 9 shows the data of two FDs as examples. In other words, it is suggested from the relationship between the RTK-GPS and the center of gravity of received light by the FD, that it has sensitivity to the size of the focused spot in the vicinity of the center of the visual field of the FD. The plot shifts horizontally from the solid line as shown in Fig. 10 if the field of view of our assumed FD and the actual field of view deviate.

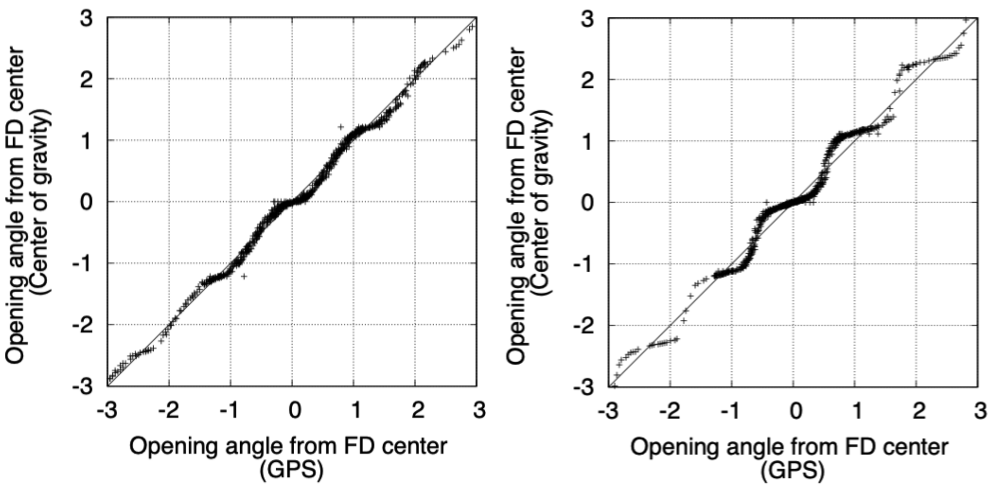

Figure 10: Correlation of the opening angle of the center of field of view of RTK-GPS and that of the center of gravity detected with FD in two FDs.

4. Analysis

The consider the case of an ideal condition where light is collected at one point was considered. The left figure of Fig. 11 shows the relationship between the pixel position (azimuth angle) of the

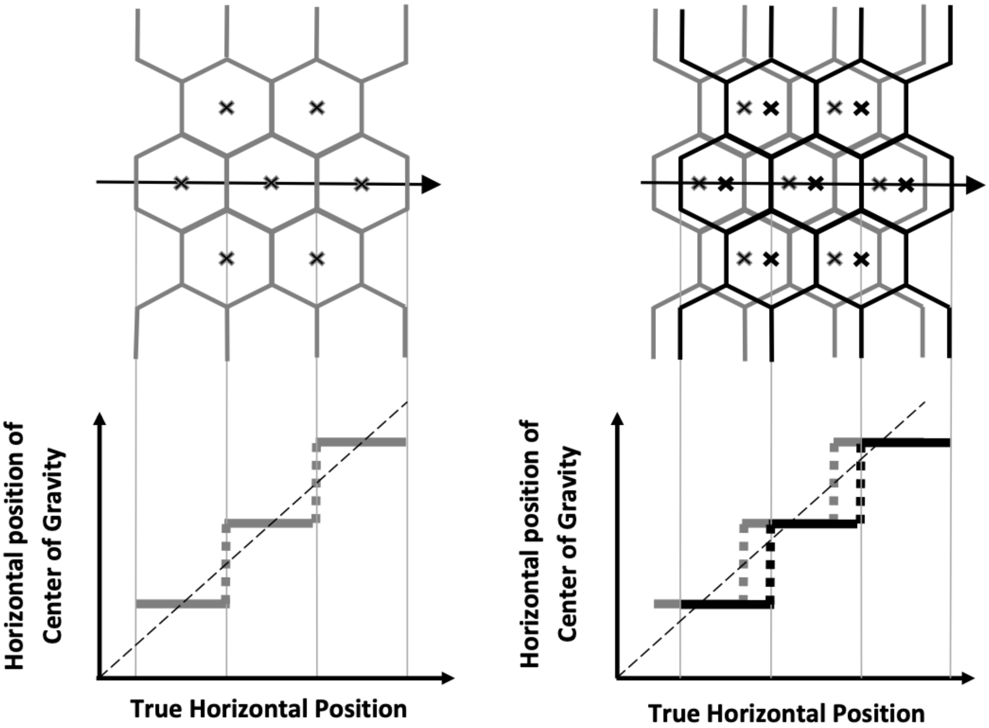

Figure 11: Position dependency of observation data when focusing to the minimum on the *camera*.

FD and the center of gravity of the received light, when the field of view of the FD is as we understand and ideally focused to one point. If the field of view of the true FD is different from the known one, the positions of the steps of the data shift as shown the right of Fig. 11. In fact, the image of the light source has a spread and blur, as shown in the Fig.10. The true direction adopted positioning by RTK-GPS. The pointing direction of the telescope is determined by its center. Also, since the FD is a reflecting telescope, coma aberration will affect at the periphery of the field of view. For this reason, only the data of the pixel at the center of the field of view was extracted. To understand the data shift, the GPS position is subtracted from the position of the light receiving center of gravity. Because the pixel shape of FD is hexagonal, it evaluates the shift of data in three directions and determines the true pointing direction. Figure 12 shows an example of this analysis. The shift of pointing direction of this example is shown the dotted hexagon that is left-side of Fig. 12.

5. Conclusion

The Opt-copter was developed as a calibration device for FD. The Opt-copter is equipped with various GPS modules for flight control, positioning and light emission timing. It is possible to measure the difference in light concentration for each FD, and the direction of field of view using the Ops-copter. In the future, it will be necessary to accurately quantify the optical properties of previously measured FDs, and operate for another FDs.

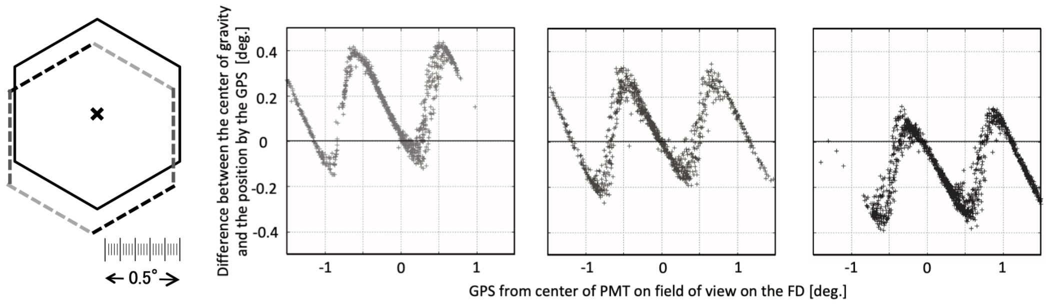

Figure 12: The example of the shift of the pointing direction by this analysis.

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