Progress Towards a Cross-Calibration of the Auger and Telescope Array Fluorescence Telescopes via an Air-borne Light Source

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Abstract: The optical calibration of the fluorescence telescopes is a significant contribution to the overall uncertainty of energy measurements made by the Pierre Auger Observatory and Telescope Array Project. Some sources of uncertainty, such as the fluorescence yield in air, affect both experiments similarly. However, the optical calibration of the fluorescence telescopes is a source of independent uncertainty. The Pierre Auger and Telescope Array collaborations have taken initial steps to establish a relative end-to-end optical calibration of the fluorescence telescopes. An Octocopter carrying a portable light source has been flown in front of fluorescence telescopes at both Pierre Auger and Telescope Array sites. Laboratory calibration measurements of the light source before and after the flights provide a common baseline for the relative end-to-end calibration. We expect this system will lead to a common photonic calibration for both experiments. After giving a brief description of the UV light source and the Octocopter used for the measurements, the parameters and the calibration procedures for the light source will be discussed. First results on telescope images of the light source will be presented.

Keywords: Telescope Array Project, Pierre Auger Observatory, fluorescence telescopes, calibration, light source, Octocopter, Ultra High Energy Cosmic Rays, UHECR, cosmic rays

1 Introduction

The Pierre Auger Observatory and Telescope Array Project experiments study cosmic rays at the highest energies. [1, 2] These experiments combine air fluorescence telescopes with a large array of surface detectors. The energy scale of both experiments is derived from the air fluorescence measurement which uses the Earth's atmosphere as a calorimeter. At present, Auger and Telescope Array appear to have an energy scale discrepancy of about 20%. [3] Some systematic uncertainties are known to affect the energy determination similarly for both experiments. However, one area where systematic uncertainties are expected to be largely independent is the photonic scale. It may be possible to reduce the apparent discrepancy between the experiments by comparing the response of the air fluorescence telescopes to a well understood and calibrated, portable light source. [4]

Such a source, a flying isotropic UV light source has been developed at Karlsruhe Institute of Technology (KIT). [5, 6] It has been in use at the Auger site in Argentina since 2010. [7] This portable light source is presently undergoing careful evaluation of isotropy, pulse rate and temperature dependence, and temporal stability.

The source is carried by a remote controlled flying platform called an Octocopter (Mikrokopter). [9, 10] The Octocopter is piloted via remote control and it includes GPS navigation and a magnetic compass, enabling it to fly to a pre-programmed position and maintain a stable position ($\sim$0.5m) and orientation ($\sim 5^\circ$) under favorable conditions. Additionally, pressure sensors are used to improve altitude accuracy and stabilization. Using this system we can accurately position a well understood light source within the field of view of both Auger and Telescope Array air fluorescence telescopes to compare their relative response.

2 The Octocopter

The Octocopter has its eight motors mounted in a circle with a diameter of 80cm. It has a maximum payload capacity of about 1kg. However, the weight of the payload significantly affects the available flight time. Since the calibration flights must be made in the dark of night when the fluorescence telescopes operate, LEDs were mounted on bottom of the arms supporting the motors. Green LEDs were installed on the arms in the forward direction and yellow LEDs were used on the remaining arms. See Figure 1. The navigation lights enable simple visual verification of position and orientation and can be switched on and off via remote control.

The Octocopter is typically flown to a distance of 1000m from a telescope where it maintains a stable position and orientation. When directed the light source emits a series of UV flashes at a rate of 1Hz. An on-board computer sends GPS information, temperature, optical pulse settings, and other data back to a base station via a wireless link where it is recorded for later analysis.

We have conducted three campaigns of flights. During the flights the on-board GPS recorded a typical positional stability of less than 1m under good flying conditions (0.06° at 1000m). The manufacturer data sheet indicates a systematic uncertainty in the absolute position of 2.5m. (0.14°). We plan to independently evaluate the absolute positioning accuracy during future campaigns.

3 The Light Source

The flight time of the Octocopter depends strongly on the weight of the payload. Therefore, it is important that, in addition to being isotropic and stable, the source should be light-weight. Based on simulations and experiments, the

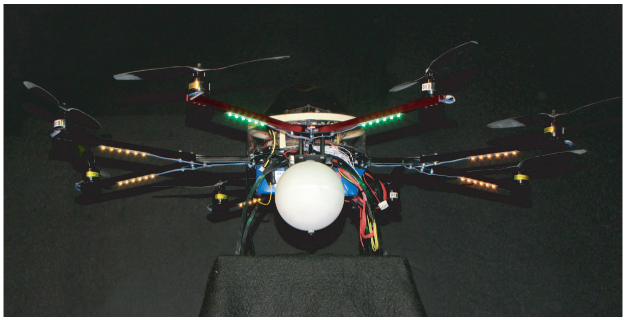

Figure 1: The Octocopter with the light source suspended below it. Green LEDs indicate the forward direction.

light source was built using a twelve sided ABS plastic dodecahedron. The body was coated with Tyvek and a UV LED [11] was mounted at the center of each of the hexagonal faces. To further improve isotropy, the source is surrounded by a diffuser made of a thin spherical shell (r=50mm) of polystyrene etched with acetone. The total mass of the completed light source was less than 150g. The full system, including light source and batteries, allows for a maximum flight time of 15-20 min.

The UV LEDs provide 55mW of radiant flux at 350mA with a spectrum that peaks at 375nm with FWHM of about 10nm and a tail extending to 410nm. The LEDs emit light out to (∼ ±90°). However, they have a stronger emission peak in the forward direction (±10-15°) and a weaker broader peak (∼80% of the strong peak out to ∼ ±60°). Simulations of a similar source configuration which takes into account the mean light distribution pattern of the UV LEDs and their placement on the dodecahedron indicates deviations from isotropy should be of order 4% over the sphere. [6]

The current to each LED is individually controlled to compensate for variations in the LED intensities. There are six pre-programmed settings of pulse amplitude and variable width (2-64μsec) which can be used to illuminate the telescopes. The six standard settings span a factor of 10 in total intensity. The light pulse is triggered by the PPS signal of the GPS.

4 Source Calibration

A number of measurements have been performed to study effects that could influence the light intensity observed by the fluorescence telescopes. The main light source test bench is located at Karlsruhe. At KIT the spherical light source and a photodiode are mounted on an optical bench with a maximum separation of 2.5m. To block reflected light, one baffle (66mm diameter) and a black curtain are centered between them. The light from the sphere is measured with a NIST calibrated silicon photodiode, model UV100. NIST calibrates these detectors using a DC light source. [8] For the peak wavelength of the light source (375nm), NIST states a spectral power responsivity of 0.1293A/W with a relative combined uncertainty of 0.45% (for DC operation). The photodiode is equipped with a round baffle to reduce the active area to the homogeneous central region (0.5cm^2). The pulsed signal from the photodiode is then measured with a Keithley model 6514 electrometer that is readout via a USB connection.

The effect of temperature on the LED's output has been measured in the lab at KIT. The results, shown in Figure 2, show that the rate of change is dependent upon the driving amplitude for the LED. At present, this amplitude dependence is not well understood and studies are ongoing. At the highest setting, A5, the change is about -4% per 10°C. To allow one to make corrections for temperature dependence, the temperature inside the sphere and near the electronics are recorded.

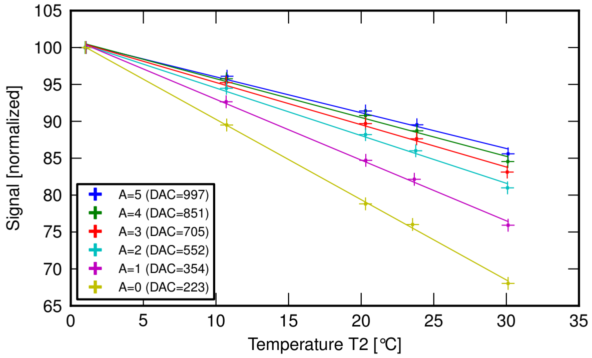

Figure 2: Relative signal strength from the Octocopter light source as a function of the temperature. Measurements were made at the DAC settings of the six standard amplitudes, A0 being the lowest and A5 the greatest. The amplitudes at each DAC setting are normalized to 100% at 0°C.

As the photodiode used for calibration of the source in the laboratory is considerably less sensitive than the air fluorescence telescopes, we must measure in the lab using a significantly higher pulse repetition rate of 1.1 kHz (900μsec period) *vs.* 1.00 Hz in the field. Initial studies of the dependence of the light output on the pulse rate suggest a correction of about -3.5% is required for field measurements. See Figure 3. The electrometer is configured to measure in 100msec intervals, each measurement triggers a pulse generator that in turn produces a burst of 100 triggers (90msec total) for the light source electronics. The 100 pulses are integrated to produce a measurement of total charge.

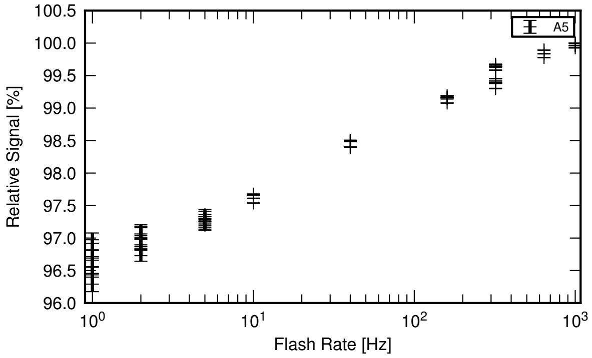

Figure 3: Relative signal strength from the Octocopter light source as a function of the flash rate. (Source amplitude setting 5)

Some tests of isotropy (in the forward direction) have been performed by rotating first in azimuth and then sepa-

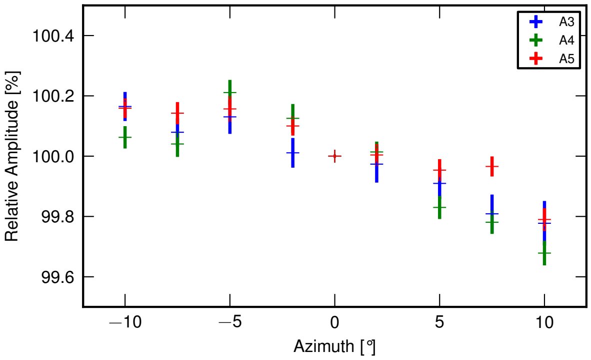

Figure 4: Relative signal strength from the Octocopter light source as a function of the azimuthal rotation angle from the forward direction. (Source amplitude settings A3(blue), A4(green), and A5(red))

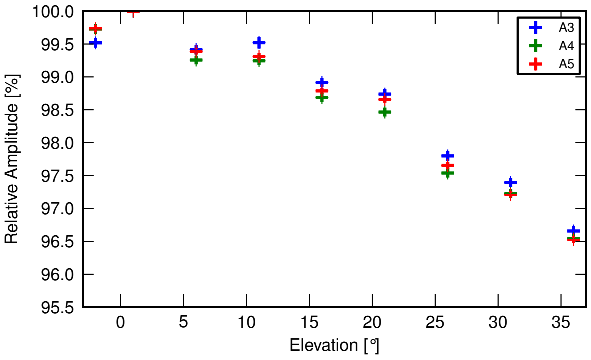

Figure 5: Relative signal strength from the Octocopter light source as a function of the elevation rotation angle from the forward direction. (Source amplitude settings A3(blue), A4(green), and A5(red))

rately in elevation. For rotations less than ±10° from forward in azimuth, the relative amplitude changed by about 0.2% (Figure 4). For elevation rotations, the relative amplitude changes by about 0.2% for a rotation of 10° and <3.5% for a rotation of 35° (Figure 5). This is consistent with the expectation from simulations noted earlier, however, more extensive evaluations are underway.

To verify that any remaining reflections from the walls can be neglected, we checked the $1/r^2$ behavior of the setup for distances between 105cm and 245cm. The data was fitted with a $1/r^2$ function with constant background and a small, constant offset in r. The results showed that there is no significant contribution from the background light.

To monitor the stability of the light source, independent measurements of the light source were performed at the University of Utah before and after each of the two campaigns at the Telescope Array site in Delta, Utah. These lab measurements took place on 2012-10-11, 2012-10-18, 2013-03-12, and 2013-03-21. After correcting for temperature, the four Utah measurements, under stable laboratory conditions, agreed to <1% relative to the mean.

For the Utah measurements, the source was mounted inside a dark box at a fixed distance (∼2.3m) from an NIST calibrated photodiode. It is important to note that this is a different photodiode from the one used for the measurements at Karlsruhe. Internal surfaces of the dark box were covered with low reflectance (black) cloth or flat black paint. In addition, a tube of black corrugated (egg carton) foam lined the optical path between the source and the photodiode to eliminate reflections. The NIST calibrated photodiode #G696 includes a precision calibrated aperture ($50.12\pm0.05\text{mm}^2$). The photodiode responsivity was measured at NIST in 5nm steps between 200nm and 1100nm. In the wavelength region near the peak of the source (375nm), the relative expanded uncertainty (k=2) of NIST photodiode #G696 responsivity is <1%. [8]

The signal from the photodiode was measured using a Keithley model 6485 picoampmeter. The picoampmeter recorded the mean current produced by series of flashes (period = 900μsec). As with the measurements at Karlsruhe, the system at Utah was configured to use a 100ms measurement interval. However, due to limitations of the hardware, instead of generating bursts of 100 triggers, an effectively continuous burst of 3000 triggers was generated. As a result, a single measurement cycle may contain either 111 or 112 flashes. This variation in the number of measured flashes contributes ∼0.1% to the measurement uncertainty. The temperatures inside the sphere and near the electronics were recorded to enable corrections for temperature dependence.

As a simple check of the charge measurement using the picoampmeter, a simple current source was constructed using a Lecroy 9210 Pulse Generator in combination with a 1.00GΩ, 1% resistor. This enabled the generation of 8μsec duration current pulses with total charge in the lower range of that obtained from the light source and photodiode. Current pulses were generated and measured using the same software and identical settings to those used during the measurement of the light source. The measured charge per pulse for the simple current source agreed with the expected value to ∼1%.

Finally, after correcting for the temperature dependence of the source, measurements performed in the laboratories at Utah and Karlsruhe appear to agree to better than 2%. However, it is important to recognize that a number of potential sources of systematic uncertainty affecting measurements in the field remain under investigation.

5 Flights at the Auger Site

Octocopters have been flown at the Auger site in Argentina with various light sources for a series of tests since 2008. The Octocopter was flown at the Auger site with the current light source, as a part of this series of tests during a campaign in November 2012. The measurements took place shortly after the October series of flights at the Telescope Array site in Utah. This period of time was selected because weather conditions and temperatures could be expected to be similar for the northern (Telescope Array) and southern (Auger) hemisphere sites.

During the tests, the Octocopter flew inside the field of view of the 4th telescope located in the Los Leones building. This particular telescope has been extensively studied during previous Octocopter campaigns and its optical properties are believed to be well understood. The measurements took place during two nights 2012-11-5 and 2012-11-10 and included participants from the Telescope Array group.

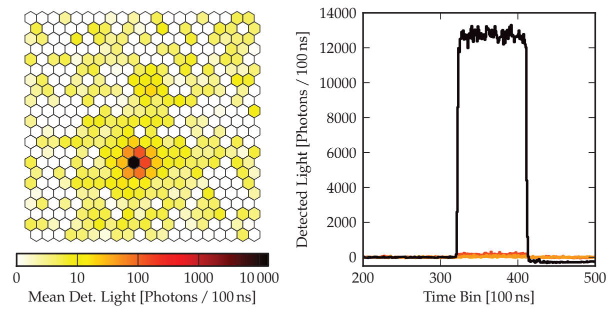

Figure 6: Event Display for an Octocopter light shot at the Auger Los Leones telescope site. The light level in the PMTs is shown at left, while the signal trace (photons/100ns) is shown at right.

Pixels in the center (column 10 and row 10), on the side (col. 17, row 10) and in the corner (col. 17, row 4) of the camera were illuminated from a distance of 1000 m with over 1100 flashes each. An event display from these flights is shown in Figure 6. Summing the signals over many flashes enables measurement of the point spread function down to a factor of 10^{-4} of the peak intensity. [7] The light source was also measured at KIT before and after this campaign. The observed change in intensity was $<2\%$.

6 Flights at the Telescope Array Site

In October 2012 and March 2013 a team from the Auger collaboration including KIT Octocopter experts visited the Telescope Array site in Utah to conduct campaigns of Octocopter light source flights. The team worked along with a researchers from the Telescope Array. The first test flights were conducted on 2012-10-14 at distances of 350m and 1000m from telescope 7 at the Black Rock Mesa site. The external temperature was about 0°C. Data was recorded using five of the six standard source settings. The Octocopter was positioned near the center of pixels 33, 73, 77, and B3 in telescope 7. Pixel 77 is located near the center of the camera and pixel 33 is half way to the corner. Pixel 33 would be expected to be more affected by spherical aberration. Pixels 73, 77, and B3 are equipped with a YAP to monitor the PMT response. [12, 13, 14] We note that pixel 77 in each camera is the telescope standard CRAYs calibrated PMT. [15] Additional flights were flown in the FOV of nine pixels the following two nights along with flights in pixel 77 at telescope 5. During these flights the highest light setting (A5) was used.

The Auger/KIT team returned to Utah for a second campaign in March, 2013. During this visit, there were only two nights of flights due to weather and conflicts with other tests. On 2013-03-16, the Octocopter flew in the Field Of View (FOV) of telescope 7 at the Black Rock Mesa site at a distance of 1000m. It hovered in the FOV of pixels 77, B7, 33, and B3. It also two flights with sweeps across the FOV of several PMTs. On 2013-03-19, it flew at a distance of 1000m in front of telescope 5 in the FOV of pixels 77 and 33.

7 Summary

Researchers at KIT have developed a sophisticated flying light source that can be used for *in-situ* optical calibrations of fluorescence telescopes. Measurement campaigns have been performed using this same equipment at the Telescope Array site (2012-10 and 2013-03) and at the Auger site (2012-11). Work is underway to understand and control systematics of the measurement to a level enabling productive comparisons between the Auger and Telescope Array photonic scales. Measurements of absolute light intensity, temperature dependence, rate dependence, and isotropy give us confidence these measurements will enable us to reduce the difference between Auger and Telescope Array photonic scales. The analysis of these datasets collected at the Auger and Telescope Array [16] is in progress and the results will be compared.

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