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The XY Scanner – A Versatile Method of the Absolute End-to-End Calibration of Fluorescence Detectors

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One of the crucial detector systems of the Pierre Auger Observatory is the fluorescence detector composed of 27 large-aperture wide-angle Schmidt telescopes. In the past, these telescopes were absolutely calibrated by illuminating the whole aperture with a uniform large-diameter light source. This absolute calibration was performed roughly once every three years, while a relative calibration was performed on a nightly basis. In this contribution, a new technique for an absolute end-to-end calibration of the fluorescence telescopes is presented. For this technique, a portable calibrated light source mounted on a rail system is moved across the aperture of each telescope, instead of illuminating the whole aperture at once. A dedicated setup for the absolute calibration of the light source has been built, which uses a combination of NIST traceable photodiodes to measure the mean intensity and a PMT for pulse-to-pulse stability tracking. As a result of these complementary measurements, the pulse-to-pulse light source intensity can be known to the 3.5% uncertainty level. The analysis of the readout of the PMT camera at each position of the light source together with the knowledge of the light source emission provides an absolute end-to-end calibration of the telescope. We will give a brief overview of this novel calibration method and its current status, as well as preliminary results from the measurement campaigns performed so far.

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[*] Presenter

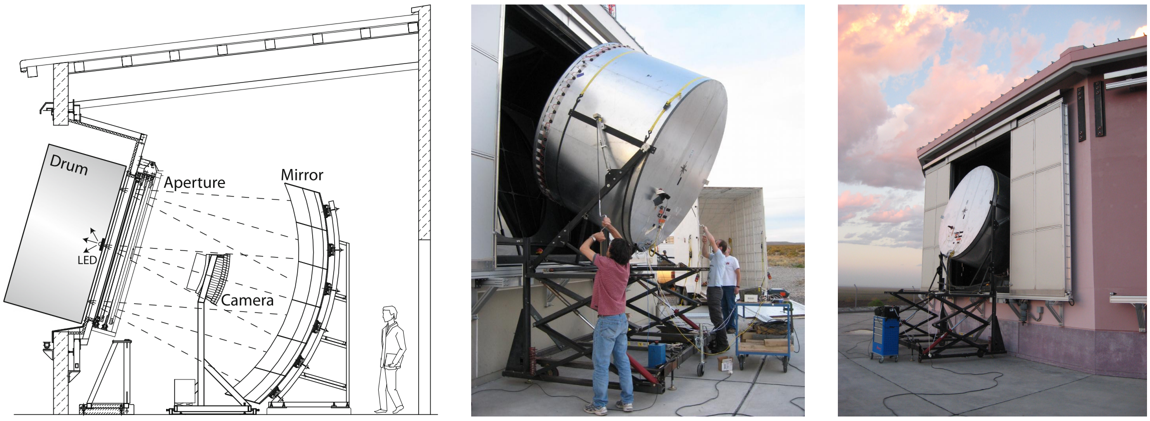

Figure 1: Schematics (left) and pictures of the installation (middle) and the measurement position (right) of the large-diameter calibration light-source (*drum*). Schematics is taken from Ref. [2].

1. Introduction

The Pierre Auger Observatory [1] consists of a surface-detector array (SD) employing 1660 water-Cherenkov detector stations distributed across an area of ~3000 km^2 and overlooked by 27 large telescopes located at four different sites, forming the fluorescence detector (FD). These two detector systems enable the observation of cosmic-ray induced air-showers by a hybrid approach. The large SD array samples particles reaching the ground, measuring a footprint of the air shower. Additionally the FD detects the fluorescence light which is emitted by the air above the ground array upon passage of charged shower particles. The detection of the shower-induced fluorescence light is then used to reconstruct the longitudinal profile of the shower. The total energy deposited by the air shower, equal to the energy of the primary cosmic ray, is directly proportional to the integral of this longitudinal profile. For this purpose, the exact conversion of a measured signal by the FD camera to an incident photon flux at the aperture window has to be known.

The FD telescopes of the Pierre Auger Observatory consist of a 440 pixel PMT-camera which is located at the focal plane of a large spherical mirror. Each 100 µs pixels are read out via a flash analog-to-digital converter. The aperture window has a diameter of ~2.2 m and is covered by a filter which is transparent only to UV photons with wavelengths between ~290 and ~410 nm. In addition, the filter protects the interior parts of the telescopes from wind, dust, and rain. Behind the filter, a corrector lens is installed, which partially corrects for the spherical aberration of the mirror. To reduce weight, cost, and construction effort, the corrector lens is build as a ring covering only the outer ~25 cm of the aperture.

For an absolute end-to-end calibration of the FD telescope the entire aperture is illuminated with a known photon flux and all pixels of the camera are read out simultaneously. The known photon flux together with the signal captured by each PMT provides a calibration constant for each individual PMT. These calibration constants include all effects induced by optical components of the telescope, like e.g. the transmittance of the filter, reflectivity of the mirror, multiple reflections within the telescope, and also various PMT effects such as e.g. quantum and collection efficiency, amplification gains, and the digital conversion factors.

In the past the absolute calibration of the FD telescopes was performed with a 2.5 m diameter uniform light source which covered the entire aperture of the telescope [3, 4]. This light source, called *drum* because of its shape and appearance, was directly mounted on top of the UV filter of the FD telescope. Drawing and photos of the installation of the *drum* are shown in Fig. 1. Because of its sheer size, handling, installing, and operating the *drum* is rather laborious and for this task requires help of several persons. The rather large amount of personpower needed to perform the absolute FD calibration with the drum was one of the main reasons why the calibration of the FD telescopes was performed rather infrequently, only roughly once every three years. However, a relative calibration, which is executed at the beginning and end of every data-taking night, tracks the absolute calibration over time and thus provides a reliable calibration of each telescope for the nights between the drum absolute-calibration campaigns. The results from the latest drum calibration-campaign show that the relative calibration system delivers excellent tracking ability. In fact, the difference between the tracked calibration constants and the absolute calibration constants obtained during that latest drum calibration-campaign was on average less than 1%.

2. The XY Scanner

In the following a novel technique of performing the absolute calibration of the FD telescopes is introduced and discussed . This new absolute calibration system employs a portable light source which is much smaller than the *drum* introduced above. Its small size enables us to transport the source easily between (a) the FD telescopes and sites and between (b) the Observatory and calibration laboratories on other continents to perform precise measurements of the source properties and its characteristics. More details on the light source are given in Section 3.

As a consequence of the small physical size of the light source, its output window is much smaller than the aperture of the FD telescopes. To overcome this difference in sizes we move the light source across the aperture window and in this way resemble the illumination of the entire aperture like it was done for the *drum* calibration.

The system which moves the light source in front of the aperture is called the *XY-Scanner*. It consists of several motorized linear stages which, two stages are mounted vertically as Y-axes and one stage is mounted horizontally as X-axis. The two Y-axes are installed permanently in the aperture box, left and right of the aperture opening while both ends of the X-axis are mounted onto the sliding carriages of the Y-axes. The horizontal X-axis is only installed for calibration measurements with the *XY-Scanner* otherwise it is stored inside the FD telescope building. For their protection the Y-axes are covered by a metal shielding during most of the time when no calibration measurements are performed. We decided to employ the drylin® W profiles produced by the company igus [5] as linear stages for all axes. These components are designed to be maintenance-free and very insensitive to influences such as dirt, water or heat. These characteristics make the drylin® components a almost ideal fit for the rough environment of the Argentinian pampa. A photograph of a complete *XY-Scanner* system installed at a FD telescope is shown in Fig. 2. To evade synchronization between the motors operating the two vertical Y-axes, both Y-axes are driven by a single motor located at the lower center of the aperture box. The Y-axes and the motor are mechanically connected via a shaft. The motor for the X-axis is directly attached to the its right end. Both axes are equipped with a braking system which is enabled during actual data-taking. Meaning, once the light source moved to its desired position both motors are switched off and the brake system holds everything

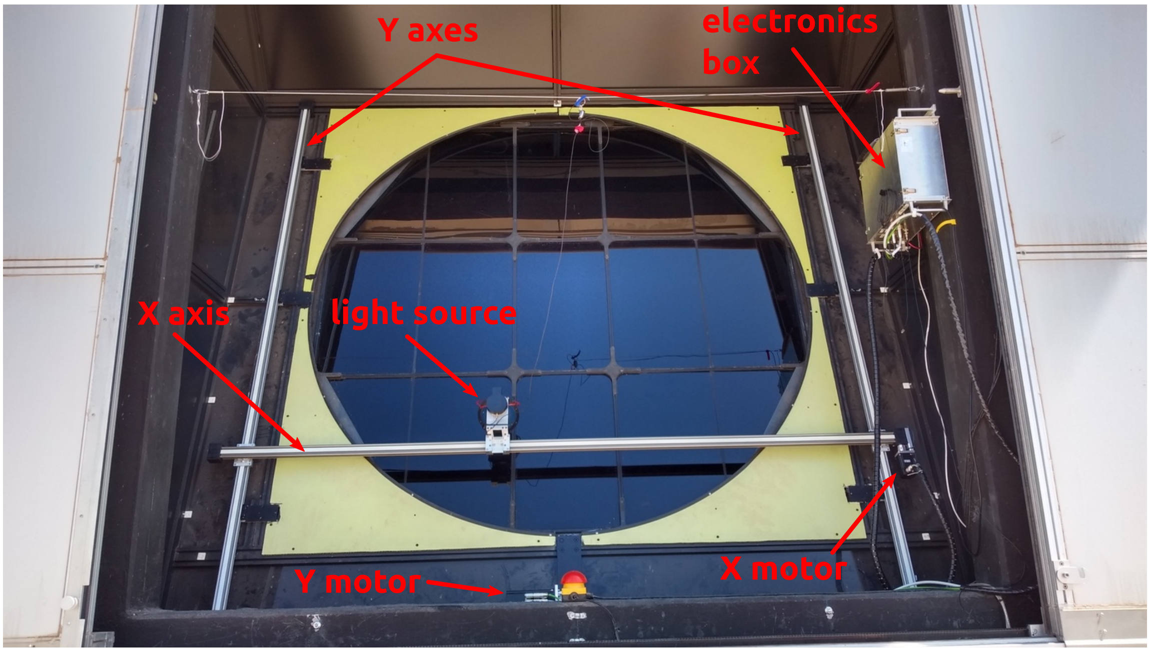

Figure 2: Photograph of a complete XY-scanner system installed onto an aperture of a FD telescope. All important components are labeled.

in position. With this procedure, possible electromagnetic interference from current flows within the motors are reduced to a minimum. The whole positioning system has a relative precision in the sub-millimeter range and automatically corrects for possible lost steps during all movements.

Status at the Pierre-Auger observatory So far we have installed 10 *XY-Scanner* system at three different FD sites and we plan to equip all 27 FD telescopes of the Pierre-Auger observatory with an *XY-Scanner* system in the foreseeable future. In fact, the material needed for the installation for the remaining 17 system is already stored at the central campus in Malargüe and will be probably installed in late 2021 or 2022, depending on the situation with the global pandemic. Once all 27 FD telescopes are equipped with a *XY-Scanner* system, we aim to have regular calibration campaigns and estimate the absolute end-to-end calibration on a yearly basis.

3. The Calibration Light-Source

As light source for the *XY-Scanner* we employ a ~13.5 cm (5.3") diameter general purpose integrating sphere of the type 3P-GPS-053-SL manufactured by labsphere [6]. This integrating sphere has one large exit port of ~6.35 cm (2.5") diameter but which is reduced to ~5.04 cm (2") by a port reducer. In addition there are two smaller ~2.54 cm (1") diameter ports positioned in a plane parallel to the exit port. For time of measurements of a FD telescope, the exit port faces towards the aperture window of that telescope while the two smaller ports are equipped with so called *heads*. In Fig. 3-left a photograph of the integrating-sphere light-source installed at a *XY-Scanner* system is shown. One of theses heads holds a Hamamatsu S1336-44BQ photo-diode (PHD) which monitors the pulse-to-pulse stability of the light source itself, but is not considered for any absolute

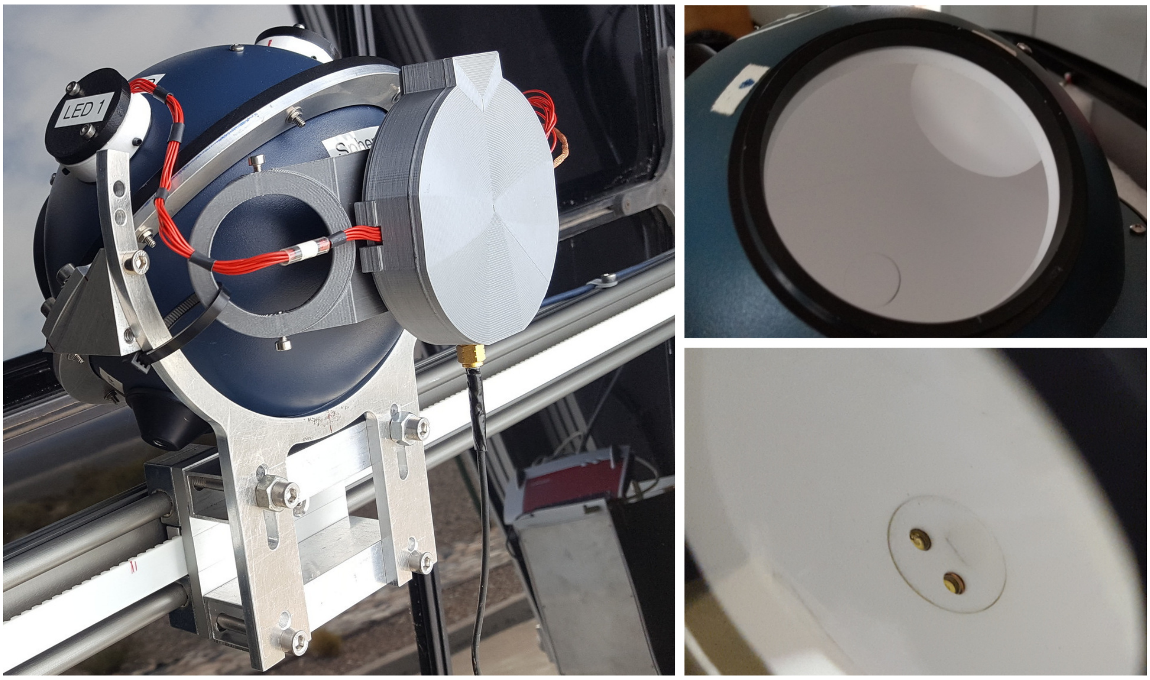

Figure 3: *Left:* Photo of the integrating-sphere light-source mounted in front of one FD aperture at a *XY-Scanner* system. *Right:* Photos of the two baffles. The upper photo shows the classic baffle covering the entire LED head. A photo of the modified baffle which only covers one of three LEDs is printed below.

calibrations. The other head carries three light-emitting-diodes (LEDs), emitting at a wavelength of $\lambda \approx 365$ nm of the type UVLED365-10E made by Roithner Lasertechnik [7]. These three LEDs mounted in that head are not operated simultaneously but each of them has its own purpose. The first LED is used for test measurements in laboratories, the second one is used to track ageing effects of the other LEDs as well as the interior material of the integrating sphere itself, and the third LED is the actual light source used for calibration measurements. Both, the PHD and all three LEDs, are mounted into temperature stabilized copper disks which are heated to and stabilized at 30°C. We chose this temperature setting to be well above the excepted ambient air temperature during nights at the FD sites in the Argentina. Therefore, it is sufficient to provide the heads with heating only to stabilize them at 30°C and no cooling is required, which would make the design of the head much more complicated. The readout of the PHD, monitoring and adjusting the temperatures, as well as operating the LEDs is performed by a micro controller of the MSP430 family. The micro controller, together with all other required components is installed onto a printed circuit board which is mounted outside the integrating sphere. The gray box on the back of the sphere in Fig. 3-left contains the micro controller and the circuit board. A single coaxial cable provides power to the board and in addition serves as trigger input line. Setting up the parameters of the light source and transferring data is realized via a wireless connection.

In the classic(?) version of the integrating sphere (as manufactured by labsphere) there is a so called baffle installed inside which prohibits direct light emitted from the LEDs to leave the sphere without any internal reflections. This baffle is a rather large shield located next to the port into which the LED head is plugged in. As a negative side effect this baffle influences the emission

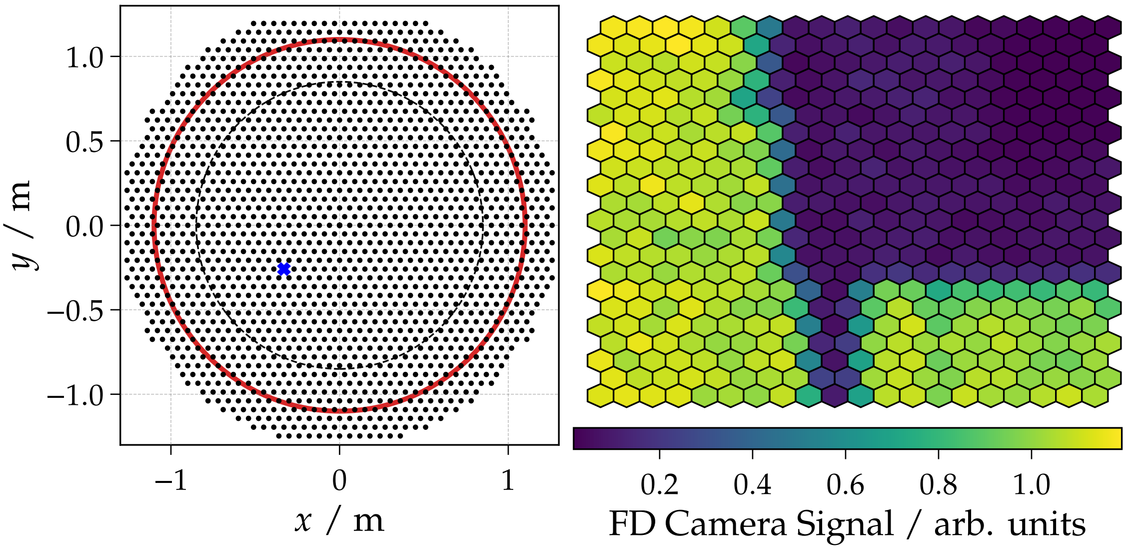

Figure 4: *Left:* All positions reached by the light source in front of the aperture of a FD telescope during a *XY-Scanner* measurement run are plotted as black dots. The red and black-dashed circles represent the edges of the aperture window and respectively the corrector ring. *Right:* Readout of the entire FD camera for the light source being at a certain position marked in blue on the plot on the left.

profile of the light source and introduces an inhomogeneity. To reduce this unwanted influence of the baffle we reduced its size to a minimum and it therefore shields only the direct emission of one of the three LEDs. The photographs on the right side of Fig. 3 show the unmodified baffle covering all three LEDs in the top photograph. The optimized, smaller baffle which covers only on of the three LEDs is displayed in the lower photograph. Size and position of the optimized baffle were estimated via simulations of the integrating sphere. In addition, to further improve the homogeneity of emission profile, a thin layer of a diffusive transmitting material was installed to cover this LED in an optimized version of the integrating sphere. With this modifications a nearly ideal Lambertian emission of the sphere is achieved.

The absolute calibration of the light source is performed in a dedicated setup built in the laboratory. This setup employs a combination of NIST traceable PHD and a PMT. The PMT is used trace the pulse-to-pulse stability of the emitted light flashes, while the PHDs measure the mean intensity of these pulses. With this complementary measurements, the absolute photon flux emitted by the light source is estimated to a 3.5% uncertainty level.

4. The Measurement Procedure

Measurements with the *XY-Scanner* are performed in a way that the light source is moved to uniformly distributed positions across the entire aperture window of a FD telescope. At each of the positions the light source emits a 5µs long light pulse of fixed intensity and all 440 PMTs of the FD camera are read out simultaneously. Reading out the whole camera is rather slow and thus limits the flashing frequency of the light source to ~1 Hz. Integrating over all flashes from all positions gives a similar illumination of the aperture window as the *drum*, as long as the positions are not

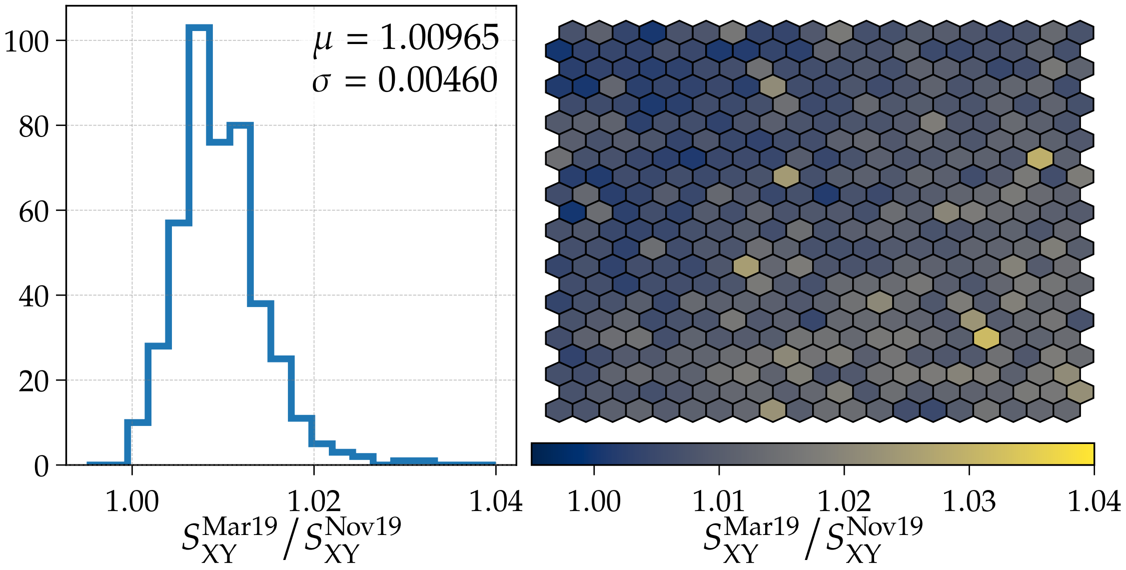

Figure 5: *Left:* Distribution the ratios of the captured signals by the FD PMTs between measurements performed in March and November 2019. *Right:* 2D pixel matrix of the ratios for the 440 individual PMTs of the camera.

spread too sparse. For an optimal coverage of the aperture window the measuring positions are distributed on a triangular grid. The distance between neighboring positions was determined on one hand to give a high coverage of the aperture opening and on the other hand to give a reasonable measuring time. For now we choose 6 cm as an optimal step size for the grid, which results in a suitable measuring time of less than one hour and gives a rather high aperture coverage of ~65% for a integrating sphere with a 5.08 cm exit window diameter. The resulting grid contains ~1700 positions, which are shown as black dots on the left side of Fig. 4. The two concentric circles in this plot illustrate the edges of the aperture opening (red) and the corrector ring (black-dashed). For the position marked with a blue cross on this plot, the captured signal of the entire camera is shown on the right side of that Fig. 4 as a 2D pixel matrix. In this illustration a part of the shadow of the camera itself is visible as a dark rectangle in the upper right corner of the plot. In addition parts of the holding structure of the camera appear as a vertical line in the lower center.

Dedicated calibration measurements with the aim of estimating the absolute calibration of a FD telescope are performed only during nights which fulfill the standard requirements for ordinary data-taking of the FD.

The calibration of the FD telescopes is only reliable if the procedure is stable in time and thus provides reproducible results. To confirm the reproducibility of the *XY scanner* results, we performed measurements with the identical settings and setup during various calibration campaigns. The comparison of the captured signal in the FD PMTs during theses measurements then provide a estimation of the reproducibility of such measurements. In Fig. 5 the ratio for measurements performed at an interval of ~9 months are presented. Both plots of Fig. 5 are based on the same underlying data, namely they display both the ratios of the signal captured in the FD PMTs during *XY scanner* measurement in March 2019 and November 2019, but in two different representations.

The left side of that Fig. 5 displays the distribution of the ratios, while the right side illustrates the signal ratio of individual PMTs as pixel matrix. On average the signals captured by each PMT differ by ~1% and therefore we conclude the reproducibility of the *XY scanner* procedure on timescale of several months.

5. Conclusion and Outlook

In this proceeding, we presented a novel method of the absolute end-to-end calibration for FD telescopes, the *XY-Scanner*. The introduced technique employs a ~13.5 cm (5.3") diameter general purpose integrating sphere as light source, which is moved across the aperture window by a motorized rail system consisting out of two vertical axes and one horizontal axis. We made modifications to the integrating sphere to improve its emission characteristics and to match its emission profile closer to that of a Lambertian emitter. The photon flux emitted by the light source can be estimated at a 3.5% level in a dedicated setup build in the laboratory. In addition we showed that the measurements performed with the *XY-Scanner* technique are reproducible on time intervals of several months.

The versatile setup of the *XY-Scanner* allows the uncomplicated installation of basically any light source, as long as its weight does not exceed the maximum weight rating of the scanner of ~2.5 kg. For example, we currently develop and test another directional light source which can be employed to measure imaging properties of the FD telescopes, like the point-spread-function.

At the time there are 10 FD telescopes equipped with an *XY-Scanner* system and we plan to install *XY-Scanner* systems on the remaining FD telescopes in the foreseeable future.

Acknowledgments ???

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