A simulation of the fluorescence telescopes of the Pierre Auger Observatory using Geant4

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Abstract. **A simulation of the fluorescence telescopes of the Pierre Auger Observatory was developed, profiting from the capabilities of Geant4 to describe complex 3D geometries realistically and to allow the required optical processes to be included in the simulation. Account was taken of the description of all optical components of the telescopes. This simulation is included in the Pierre Auger offline software framework and is being used in several studies of the fluorescence detector performance. The main features of the simulation are reviewed.**

Keywords: **Geant4 simulation, fluorescence telescope, Pierre Auger Observatory**

I. INTRODUCTION

A detailed simulation of the fluorescence telescopes of the Pierre Auger Observatory was developed, taking advantage of the capabilities of Geant4 [1], [2] to describe complex 3D geometries realistically and to allow the required optical processes to be included in the simulation. The Fluorescence Detector (FD) of the Pierre Auger Observatory is composed of 24 fluorescence telescopes, located in four buildings overlooking the Surface Detector array. Each telescope features Schmidt optics consisting of a ring shaped corrector lens placed at the entrance pupil and a 11 m^2 spherical mirror. The incoming light is focused on to a spherical camera, containing 440 hexagonal pixels made of photo-multipliers (PMT) and light guides [3].

Geant4 is a software toolkit, developed in the C++ programming language, to simulate the interaction of particles through complex 3D geometries. In Geant4 the user defines the geometry and composition of the media, as well as a primary particle and its properties. The kernel then takes care of the tracking and interactions of the primary and secondary particles throughout the defined "world", taking into account the properties of the traversed materials and the selected physical processes.

The tracking of optical photons includes refraction and reflection at medium boundaries, Rayleigh scattering and bulk absorption. The optical properties of a medium, such as refractive index, absorption length and reflectivity coefficients, can be expressed as tabulated functions of the wavelength. In addition, specific characteristics of the optical interfaces between different media can be defined using the UNIFIED optical model [4], which provides a realistic description of surface finish and reflector coatings. Complex geometries can be defined by exploiting the Constructive Solid Geometry (CSG) functionalities in Geant4, that allows to build complex solids from simple ones using boolean operations.

This simulation is included in the Pierre Auger simulation and reconstruction framework [5]. It is being used in several performance studies of the fluorescence telescopes, in particular those related to the optical spot and the light detection efficiency.

II. IMPLEMENTATION OF THE TELESCOPE COMPONENTS WITH GEANT4

Account was taken of the description of the corrector lens profile, the details of the mirror geometry, including the parameters of each individual mirror, and the different components of the camera, including light guides and photo-multipliers (PMT). The optical properties of all materials, such as the absorption length and the refractive index, are described in the simulation.

The filter at the entrance pupil of the fluorescence telescopes is implemented as a disk made of M-UG6 [6], with a diameter of 2.2 m and a thickness of 3.25 mm. The filter is positioned perpendicular to the optical axis of the telescope at $(0, 0, -10\,\mathrm{cm})$ [1]. The refractive index is set to $n = 1.526$ and the absorption length is computed from the transmittance for the filter material with a nominal value of 0.83 at a wavelength of 370 nm for a thickness of 3.25 mm.

The simulation of the corrector lens, made of BK7 glass, uses the Geant4 class `G4Polycone`. Given the lens axial symmetry this class enables the description of an arbitrary profile, by its decomposition into a sufficiently large number of straight segments. The segmentation of the corrector lens in 24 petals, each with an angular width of $14.735°$ is also implemented in the simulation. A visualization of the lens profile is shown in figure 1.

The telescope mirror, composed by 64 hexagonal elements arranged in 8 rows, is implemented in full detail in the simulation. The mirror elements are quasi-hexagonal spherical mirrors, and their shape depends on the position in the telescope mirror. To define the mirror elements, 3 to 5 (depending on the type of element) trapezoids are joined and the resulting solid

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[1]The telescope coordinate system is defined with the z axis aligned with the optical axis, pointing outwards, the y axis horizontal and the x axis orthogonal to the z and y axis, pointing downwards. The origin of this coordinate system coincides with the geometrical centre of the corrector lens.

(a)   (b)

Fig. 1.   (a) Detail of the corrector lens in the Geant4 simulation. The curvature of the corrector ring is magnified to be visible. (b) A segment of the telescope mirror. The trapezoids joined to make the mirror element are artificially displaced for better visualization.

Fig. 2.   View of the camera in the Geant4 simulation. The picture show the light guides in light blue and the PMT windows in red.

is intersected with a spherical shell, with inner radius equal to the radius of curvature of the mirror element. A visualisation of one mirror element is shown in figure 1. The positioning of the hexagonal elements emulates the alignment procedure performed in the real telescopes, with the centre of curvature of each element coinciding with the alignment point, which is located at the origin of the telescope reference frame. The optical properties of the mirror are implemented by defining the reflectivity in the interface surface between the air and the mirror. The curvature radius, positioning angles and reflectivity of each individual segment are read from a database.

The cameras of the fluorescence telescopes are composed by the light guides, the PMTs and the supporting structure [7]. The light guides are placed at the vertexes of each hexagonal PMT. In the Geant4 simulation they are made by the union of three triangular prisms, each built using the Geant4 class `G4Polyhedra`. The reflectivity at the surface interface is set to 0.9 for all wavelengths. In the simulation the PMTs include the hexagonal window and the metallic photocathode. A sensitive detector is associated to the photocathode to simulate the detection of photons. The quantum efficiency is taken into account a posteriori by applying it to the recorded signal at each pixel. Both the PMTs and the light guides are placed following the curvature of the camera. The body of the camera support and feet are also included, to correctly simulate the shadow effect. A view of the camera as implemented in the simulation is shown in figure 2.

The fully assembled telescope is visualised in figure 3 which shows photons arriving at the telescope parallel to the optical axis tracked through the various optical elements of the telescope and focused onto the camera.

III. SIMULATION OF THE TELESCOPE PERFORMANCE

The simulation is being used in studies of the performance of the fluorescence telescopes, concerning the optical spot and the light detection efficiency. Some of the results of these studies are summarized below.
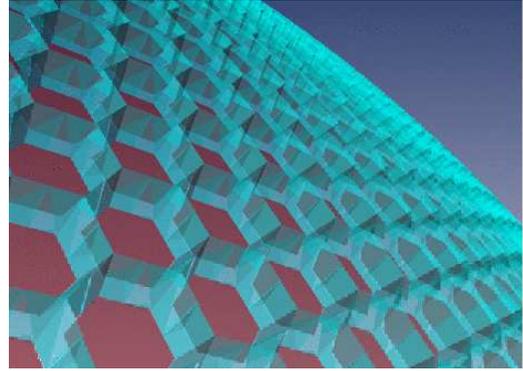
A. The Optical Spot

The telescope optics was studied by characterising the image produced on the focal surface. The photon position in the focal surface is defined by the elevation angle, $\alpha = \arcsin(x/R_{\mathrm{FS}})$, and the azimuth angle, $\beta = \arcsin(-y/R_{\mathrm{FS}})$, where R_{FS} is the radius of curvature of the focal surface and x, y the Cartesian coordinates of the photon at the camera. Beams of parallel photons were simulated at input angles, with respect to the telescope axis, of $\theta = 0°$, $\theta = 5°$, $\theta = 10°$ and $15°$, with $\varphi = 135°$ The spots observed at the ideal focal surface are shown in figure 4. For photons with an input angle of $\theta = 0°$ the spot presents an almost complete circular symmetry, which arises from the symmetry of the telescope with respect to the optical axis, only broken by the square camera body. For larger angles the central region of the spot is deformed along the same direction as the input direction of the photons. This is due to the photons passing through the corrector lens. Since the mirror is spherical, the contribution due to the photons crossing the hollow part of the lens still results in a symmetric spot, except for the region obscured by the camera. These spots obtained with the Geant4 simulation confirm the optics performance expected from previous ray tracing studies [8].

B. Photon Distribution at the PMTs

Photons crossing the focal surface reach the PMTs, directly or after being reflected by the lightguides. The position of the photons on the PMT window are shown in figure 5. In the top image the spot is contained inside the pixel, with few hits on the light guide and the centre of the pixel densely illuminated. However, when the incoming photons are focused at the vertex of a light guide the three adjacent PMTs are hit, as shown in the bottom image of figure 5. In this case a large fraction of photons is reflected at the light guides, resulting in a blind circular region centred on the light guide vertex. From these example cases it is clear that the illuminated zones of the PMTs vary with the position of the spot centre. The collection efficiency of a PMT varies along the photocathode, which can yield an additional
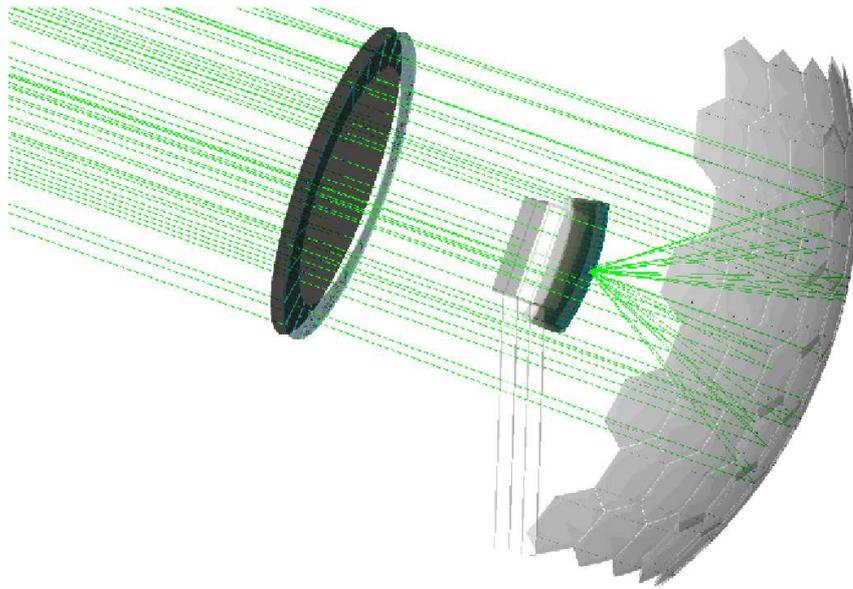
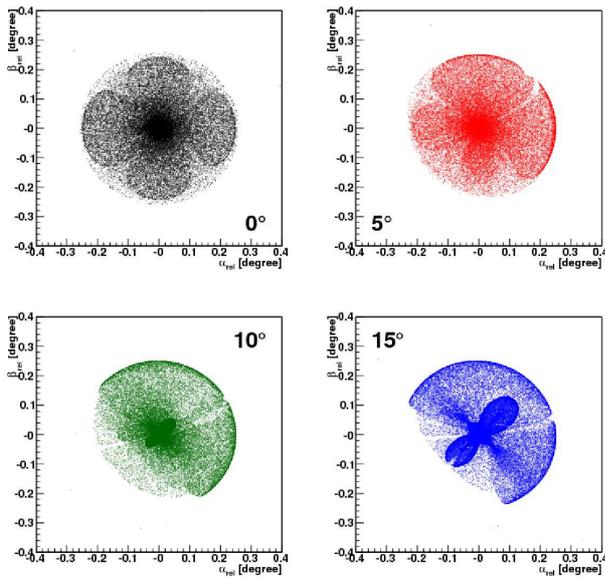Fig. 3.   View of the assembled telescope and the tracking of photons.

Fig. 4.   Spots produced at the ideal focal surface for incident angles of 0°, 5°, 10° and 15°. For each generated photon the relative position $(\alpha_{\mathrm{rel}}, \beta_{rel})$ with respect to the expected position for an ideal optical system is shown.

contribution to the overall telescope efficiency with the spot centre position. The non-uniformity of the PMT response can be taken into account in this simulation framework.

C. Comparison with laboratory data

The simulation was compared with laboratory measurements of the light detection uniformity [7] (and references therein), where a small version of the camera with seven pixels was used. Since the telescope optics is fully implemented in the Geant4 simulation and the
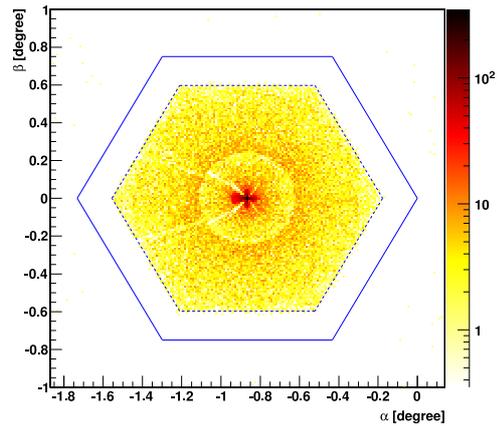
(a)
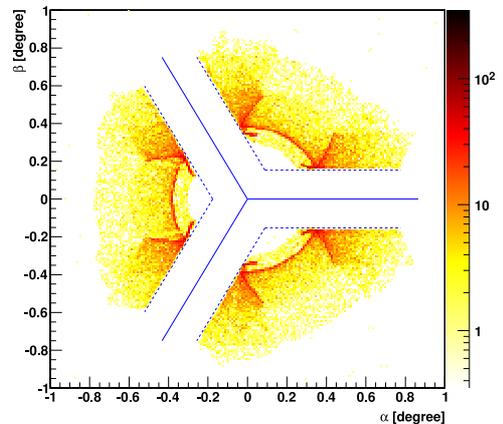
(b)

Fig. 5.   The spot seen at the PMTs. Lines are drawn to represent the pixel boundaries (solid) and the light guides boundaries (dashed). Photons simulated with the expected position at the pixel centre (a) and at the vertex of the light guide (b).

experimental setup reproduces the spot generated by the telescope optics, the measurements can be simulated by illuminating the diaphragm with parallel light rays with varying incident directions, enabling a scan of the seven central pixels. As in the laboratory measurements two scans were performed: one through the arms of the light guides and one passing over the vertexes. The efficiency, defined as the ratio between the number of photons that arrive at the PMTs and the number of generated photons, normalised to the efficiency value in the centre of the central pixel, is shown in figure 6 for the first scan. The measurements are shown for comparison. Good agreement was found in both cases. The efficiency variations are of the order of 15% over the camera surface. The result of 0.85 for the lowest value of the efficiency obtained in the measurements is reproduced by the simulation. The steep fall in the extremes of the scan in the laboratory data is due to the fact that in the laboratory setup only seven pixels were present.

IV. Conclusions

The full simulation of the 3D geometry of the telescopes of the fluorescence detector of the Pierre Auger Observatory was implemented using the Geant4 Monte Carlo toolkit. This simulation is being used in several studies of the performance of the telescopes, in particular those related to the optical spot and the light detection efficiency. The capability of describing realistically and in detail all optical elements of the telescopes contributes to deepen the understanding of the FD performance.
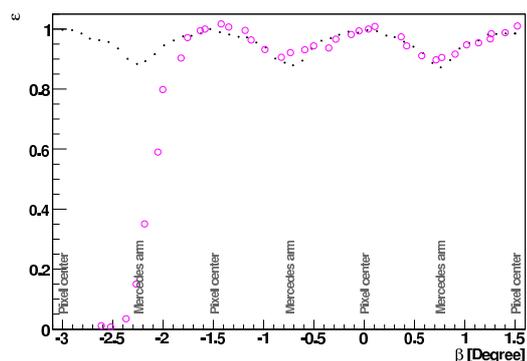

Fig. 6. Relative efficiency along a horizontal line passing through the centre of the pixels. The black dots are the simulation results and the white circles the laboratory measurements.

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