Geant4 simulation of a surface Cherenkov detector.

Carolina Filgueira Rama
Judith Reyes Martín

Simulation of a simplified Auger hybrid detector.

Auger hybrid detectors

The Pierre Auger Observatory employs hybrid detectors that combine two different techniques to measure extensive air showers produced by cosmic rays [1]. In this study, we focus on the surface detector component, which measures the Cherenkov light produced when high-energy particles traverse a water tank.

Each surface detector consists of a cylindrical polyethylene tank measuring 3.6 meters in diameter and 1.2 meters in height. These tanks are hermetically sealed and lined internally with a highly reflective coating to maximize the collection of Cherenkov photons. The tank contains 12,000 liters of ultrapure water and is instrumented with three photomultiplier tubes (PMTs) of 23 cm diameter, mounted at the top. See Figure 1 for a reference image.

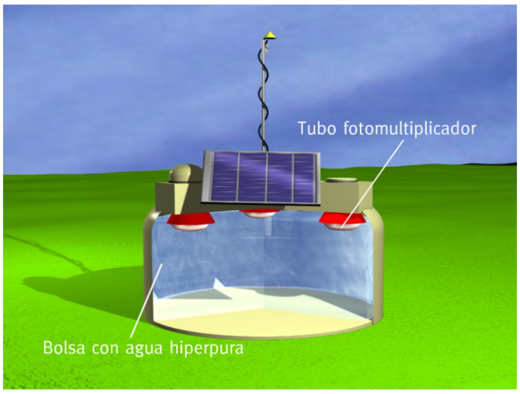

Figure 1: Surface detector of the Pierre Auger Observatory.

In this project, we implement a simplified version of the experimental setup in the Geant4 framework to simulate the production and detection of Cherenkov light inside the tank.

Geant4 simulation.

Detector construction

To implement the detector described above, we used several volumes based on the `G4Tubs` solid in Geant4. The following components were defined:

1. External plastic tank. This volume is defined by a Boolean subtraction of two `G4Tubs` solids, creating a hollow cylindrical shell that represents the plastic structure of the tank.

2. Water volume. The water is placed inside the cavity of the tank. The volume was computed from the known quantity of water (12,000 liters), assuming a density of $1\,\mathrm{g/cm^3}$. Since the internal radius is fixed by the tank specifications, the required height was calculated accordingly.

3. Photomultiplier tubes (PMTs). The three PMTs with 23 cm of diameter are placed just above the water surface. Each PMT is modeled as a thin `G4Tubs` volume with a height of 1 cm, matching the remaining space between the water and the tank lid. The PMTs are arranged in an equilateral triangle of radius 0.75 m.

The resulting detector geometry is shown in Figure 2.

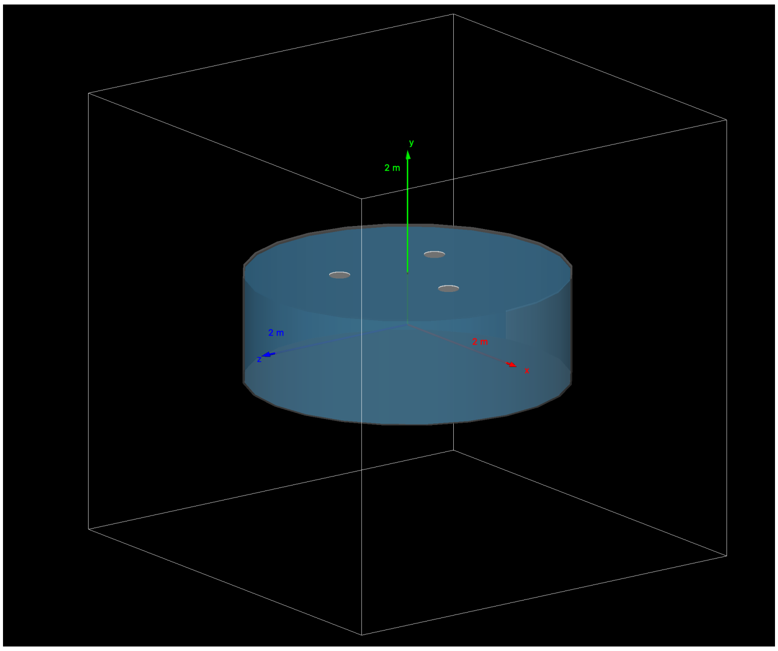

Figure 2: Detector implementation.

In order to generate Cherenkov photons, it is necessary to define the optical properties of the materials involved. In particular, the refractive index of the water inside the tank must be specified. This was obtained from tabulated data provided in [3]. The absorption length of water was also set using data from the same source.

By simulating a muon passing through the water volume, we observe the characteristic Cherenkov light cone (see Figure 3). However, to ensure that the detector behaves in a physically realistic way, it is important to maximize photon collection. To that end, we include a reflective inner lining by defining a `G4OpticalSurface` between the external plastic tank and the water, assigning it a high reflectivity.

Finally, in order to register the Cherenkov photons that reach the photomultiplier tubes, the PMT volumes are declared as `G4VSensitiveDetector` objects.

Particle generation

To simulate muons arriving from random directions within the solid angle corresponding to the upper hemisphere (above the horizon), we generate initial positions (x, y, z) uniformly distributed over the surface of a hemisphere of radius $R = 1.5\ m$, centered on the detector. This corresponds to a polar angle $\theta \in [0, \pi/2]$ and an azimuthal angle $\phi \in [0, 2\pi]$ in spherical coordinates. The momentum direction is always oriented downwards, toward the detector.

Moreover, it has been experimentally verified that the angular distribution of atmospheric muons follows a law proportional to $\cos^n(\theta)$, where n is a parameter close to 2 at sea level [2]. In this simulation, we use $n = 2$. To sample values of θ according to this distribution, we apply an acceptance-rejection method.

Results.

As noted earlier, the simulation successfully reproduces the Cherenkov light generated by muons traversing the water. This light is clearly visible before introducing the reflective inner surface. Once the reflective lining is implemented, the photons are distributed more uniformly throughout the volume, making the cone shape impossible to visualize.

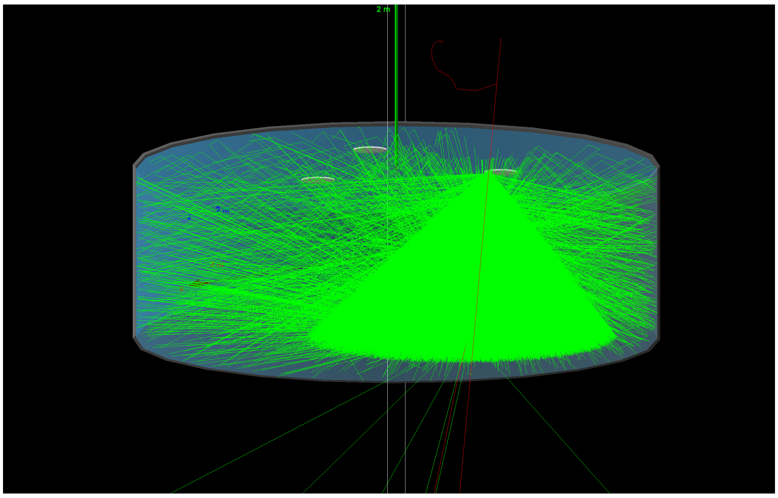

Figure 3: Cherenkov cone (before defining the internal reflective lining).

The ultimate goal of this detector is to reconstruct the trajectories of incoming muons by analyzing the first photon detections. By selecting the earliest photon arrival times and using the known positions of the PMTs, it is possible to reconstruct a two-dimensional projection of the muon's path. However, we consider this analysis to lie beyond the scope of the present project.

It is also worth noting that the number of detected photons in the simulation depends strongly on the muon trajectory. More inclined muons tend to produce a larger number of Cherenkov photons, a trend that can be observed by running the simulation with different incident angles.

References

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