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Geant4 based simulation of the Water Cherenkov Detectors of the LAGO Project

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Abstract

To characterize the signals registered by the different types of water Cherenkov detectors used by the Latin American Giant Observatory Project, it is necessary to develop detailed simulations of the detector response to the flux of secondary particles at the detector level. These particles are originated during the interaction of cosmic rays with the atmosphere. In this context, the LAGO project aims to study the high energy component of gamma rays bursts (GRBs) and space weather phenomena by looking for the solar modulation of galactic cosmic rays (GCRs). Focusing on this, a complete and complex chain of simulations is being developed that account for geomagnetic effects, atmospheric reaction and detector response at each LAGO site. In this work we shown the first steps of a GEANT4 based simulation for the LAGO WCD, with emphasis on the induced effects of the detector internal diffusive coating.

Keywords: Water Cherenkov Detector, Space Weather, Cosmic Rays, Geant4

1. The Water Cherenkov Detectors of the LAGO Project

During the interaction with the atmosphere, cosmic rays produce large cascades of secondary particles called extensive air showers (EAS). The spatial and temporal distributions of these secondary particles at ground level had been used for decades in several observatories to study the underlying mechanisms in the development of these cascades. To get a deeper understanding of this phenomena, the characterization of the detector response is crucial. Several techniques had been used at different experiments, such as complementary measurements with different type of detectors, first principles calculations and detailed simulations.

The Latin American Giant Observatory (LAGO, formerly known as Large Aperture GRB Observatory) is an extended cosmic ray observatory composed by a network of water Cherenkov detectors (WCDs) spanning over different sites located at significantly different latitudes (from the south of Mexico up to the antarctic region) and different altitudes (from sea level up to more than 5000 m a.s.l.). This network covers a huge range of geomagnetic rigidity cut-offs and atmospheric absorption/reaction levels. In the Figure 1 we show the current status of the detection network, designed to measure with extreme detail the temporal evolution of the radiation flux at ground level. It is mainly oriented to perform basic research on three branches: the extreme Universe, space weather phenomena and atmospheric radiation at ground level [1, 2]. Several scientific and academic programs are conducted within the LAGO framework in Latin America [3].

LAGO is being built and is operated by the LAGO Collaboration, a non-centralized collaborative union of more than 30 institutions from nine Latin American countries. Using observations from our WCDs, it is possible to study the galactic modulation of galactic cosmic rays from combining different ground sites, in particular it is possible to study the long-term modulation as well as transient events.

The LAGO water Cherenkov detectors are built starting from commercial water tanks with $\sim 1\,\mathrm{m}^3$ to $40\,\mathrm{m}^3$ of purified water. The passage of ultra-relativistic charged particles through the water volume produce

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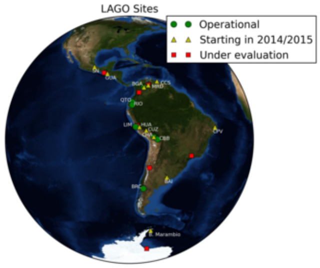

Figure 1: Current status of the LAGO detectors network in Latin America (green circles: operative sites; yellow triangles: starting/started in 2014-2015; and red squares: sites under evaluation).

Cherenkov light that is collected by a central photomultiplier tube (PMT), typically an 8-inch Hamamatsu R5912 PMT. The sensitivity to secondary gammas in the cascade is enabled by the production of Cherenkov capable electron/positron pairs within the water volume. The detector has an internal coating made by a highly diffusive and reflective fabric of commercial Tyvek®. The diffusion of Cherenkov photons in the fabric surface reduces the signal dependence on the secondary particle trajectory within the detector. A FPGA based, own designed fast analog-to-digital conversion electronics allows the operation of up to four independent detectors in a same site. This electronics is controlled by a Raspberry Pi or similar device. Additionally, the station has a temperature and atmospheric pressure sensor and a GPS board for time synchronization between different LAGO sites. The power consumption of the station is less than 11 W and is powered by solar panels and batteries. The LAGO WCD are characterized by its low cost and reliability, and a schema of this detectors can be seen in Figure 2.

2. Detector simulation

When a particle travels in a medium at a faster speed than the wavelength-dependent phase velocity of the EM field in that medium, it emits Cherenkov radiation at those wavelengths, a phenomenon which is totally independent of Bremsstrahlung. It can be seen that the number of Cherenkov photons by unit of interaction depth X that are radiated by the medium with refractive index $n(\lambda)$ in the wavelength interval $\lambda_1 \leq \lambda \leq \lambda_2$ is given by:

$$\frac{\mathrm{d}N}{\mathrm{d}X} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right), \qquad (1)$$

where $\alpha = (e^2/\hbar c)$ is the fine structure constant. In the typical wavelength range of interest for commercial PMTs, an ultra-relativistic charged particle produces ~ 30 Cherenkov photons per millimeter in pure water.

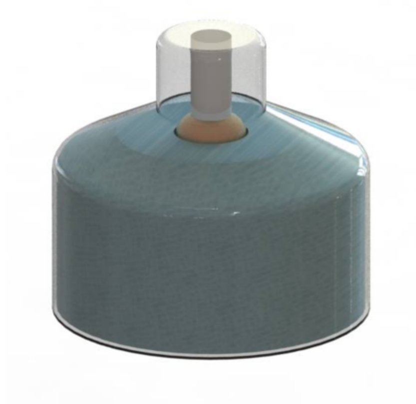

Figure 2: Typical water Cherenkov detector of the LAGO project detection network. It is composed by a commercial water tank, a single central photomultiplier tube and an internal coating made by a highly diffusive and reflective material.

The Geant4 framework [4] provides internal routines to generate Cherenkov photons based on the formula above. For each charged particle propagating through a medium it verifies the Cherenkov condition and produces photons with the corresponding wavelength distribution.

The detector simulated in this work corresponds to one of the operating detectors at the Universidad Industrial de Santander (UIS), located in the city of Bucaramanga, Colombia, at 956 m a.s.l. This detector, Guane-3, was built with a commercial water tank of radius $r = 0.515$ m and total height $h = 0.59$ m. The PMT was simulated as an hemispheric volume of radius $r_P = 0.101$ m immersed in the water volume at the center of the roof. Each Cherenkov photon impinging on the PMT surface was counted with a constant probability of 0.25 (independent of the photon wavelength), which corresponds to the approximated quantum efficiency (QE) of the Hamamatsu R5912 PMT in the range $330 - 570$ nm. Cherenkov photons with wavelength out of this range were simply discarded. For the medium we consider pure water with refractive index depending on the photon wavelength.

The inner surface coating was simulated following the guidelines given by Janecek and Moses [5]: at the code level, the routine representing the internal surface has a pointer to a table describing a particular surface. If the surface is, e.g., painted, wrapped, or has a cladding, the table includes a multiple layer with different refractive index. The Tyvek diffusive properties are simulated by using look-up tables that describe the inner sur-

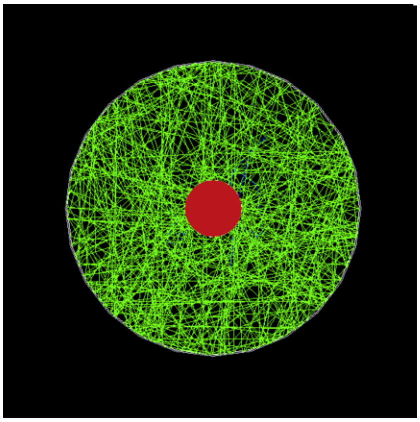

Figure 3: Cherenkov photons (green lines) produced during the propagation of a vertical muon with energy $E = 100\,\text{MeV}$ across the simulated detector volume. The simulated PMT is visible as a red mesh in the central part of the detector roof.

face properties and were constructed from experimental measures from Filevich et al. [6]

Finally vertical muons with different energies were injected trough the water volume. As an example, in Figure 3 we show the Cherenkov photons produced by a muon with energy $E_\mu = 100\,\text{MeV}$. In this case, the muon has enough energy to completely cross along the detector.

It can be deduced from equation (1) that the number of Cherenkov photons produced by the passage of a particle trough the detector only depends of the medium (water) and of the particle speed (βc). Moreover, the number of photons $\mathrm{d}N/\mathrm{d}X$ in a fixed range of wavelengths is nearly constant for large βs. Bearing in mind the properties of the diffusive material, and for a fixed detector geometry, it is clear then that the pulse shape will depend mainly in the range of each type of particle in the water volume. So we use the detector pulse shape, i.e. the time distribution of Cherenkov photons impinging on the PMT, as a clear indicator of the detector response for each type of particle. In the Figure 4 we show the averaged pulse shape produced by 200 individual vertical muons with energy $E = 5\,\text{GeV}$ for the WCD typical internal coating. By fitting an exponential function of the form $f(t) = N_0 \exp(-t/\tau)$, we obtained that the characteristic time of the pulse produced by a vertical atmospheric muon in Guane-3 is $\tau = (55.1 \pm 0.7)\,\text{ns}$, which is consistent with the observed pulse in the detector in the signal range corresponding to vertical muons.

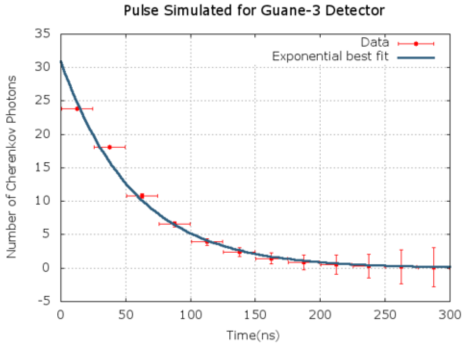

Figure 4: Simulated pulse shape produced by the passage trough the UIS detector of an atmospheric muon with energy $E = 5\,\text{GeV}$. The characteristic time obtained by fitting an exponential function (solid line) is $\tau = (55.1 \pm 0.7)\,\text{ns}$, which is consistent with the observed pulse at the detector.

3. Conclusions and Acknowledgements

In this work we show the first results of a completely based GEANT4 simulation of one of the LAGO WCD installed at the Universidad Industrial de Santander, in Bucaramanga, Colombia. By using the pulse shape as an indicator of the detector response, we obtained the averaged pulse shape produced by a vertical atmospheric muon traversing the detector volume, with a characteristic time $\tau = (55.1 \pm 0.7)\,\text{ns}$, consistent with the real muon pulse of this detector.

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