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GPU accelerated optical light propagation in CORSIKA 8

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Optical photons, created from fluorescence or Cherenkov emission in atmospheric cascades induced through high energetic cosmic rays are of major interest for several experiments. Experiments like CTA require a significant amount of computing time and funds for the simulation with CORSIKA 7.

Since individual photons don't interact they can be simulated without any order. The traditional sequential approach is simple but leads to reduced utilization of modern hardware infrastructure. The calculations done on each photon have low complexity, compared to the other aspects of the simulation. This, as well as the fact that, besides information about the photon itself, nearly no additional data is needed, favors a data-parallel approach in which several photons are propagated concurrently. The new CORSIKA 8 framework enables the implementation and verification of these methods.

With the use of dedicated high parallel acceleration hardware like GPUs the possible benefits with this data-parallel approach are even higher.

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1. Optical light in atmospheric cascades

For the observation of high-energy cosmic rays, direct observation by satellite-based experiments is currently not possible, due to their comparably low rate. Large-scale Earth-based observations, on the other hand, are hampered by the complex cascading interactions within the atmosphere. To address this problem high-quality simulations of the entire cascade are required to gain meaningful insight from the observed parameters. Large simulation samples are therefore of great importance, but in many cases can only be achieved, if at all, with massive computational and thus equally high costs. Several physical properties of the shower can be used as the observable/measurable parameters. One frequently used feature is the well detectable emission of light in the optical wavelength range in the form of Cherenkov radiation and fluorescent light within the forming cascade. With over 80 % the first is one of the most run-time intensive parts in the simulation chain, due to their very large number of individual photons.

In this work, the completely redeveloped C++17 simulation framework CORSIKA 8 [1] is used. This is the successor of the widely used Fortran simulation software CORSIKA 7 [2], which is difficult to modernize due to its age and architecture. Due to the steadily-advancing evolution of computer hardware from former single CPU cores to today's highly parallel heterogeneous systems, the previous linear and iterative approach [3] used in CORSIKA 7 is no longer optimal for today's hardware. A different approach to the GPU implementation described in the following chapters is the optimization of the previous method using vectorization [4].

Based on previous work of the author [5] and to leverage the extensive development of deep-learning hardware, like the high processing power of modern graphics processors, the development was focused on NVIDIA's CUDA [6] architecture. This should facilitate better and more simulations for future experiments.

2. Accelerated Architecture

The complete simulation chain for the generation and propagation of Cherenkov and fluorescence light emission described here is currently a Python program, utilizing PyCuda [7], which is separated from the main CORSIKA framework to allow an easier evaluation, cross-checking, and rapid changes of the developed GPU kernels. The CORSIKA output of individual particle traces is directly transferred to Python and than the GPU to processed further.

For the overall GPU side processing of particle tracks several modules could be reduced between the two different physical phenomena. On difference beside the generation itself is the "Filter Stage". Due to the fact that fluorescence emission is isotropic and not beamed like Cherenkov radiation, there is no early removal of particles applicable.

To utilize the full computational power of graphics co-processors, several special conditions must be met. The most important of these is the data- and time-parallel execution of all operations. This prohibits calculation on individual or a small number of traces, without massive performance degradation. Thus, to ensure that there is always enough data present to keep all cores active, there must be multiple parallel instances of CORSIKA present. The execution pattern for the first two operations is data-parallel at the particle track level. The subsequent operations are parallelized at the photon level.

2.1 Track Input

In the currently utilized version of the input handler, the curvature of the particle traces due to external factors, such as the geomagnetic field, is handled by the CORSIKA routines. To abstract from this, the common simplification of the particle tracks as line segments with a length corresponding to the acceptable error rate takes place. To reduce the workload on the CPU side and avoid additional branching, all traces are passed directly to the GPU, regardless of whether they can produce optical light emission.

On the GPU side, a first pass of the data applies some rough cuts in energy and charge to remove data that could create floating-point problems later on. In addition, the data is moved and restructured to allow for faster processing later on.

2.2 Filter Stage

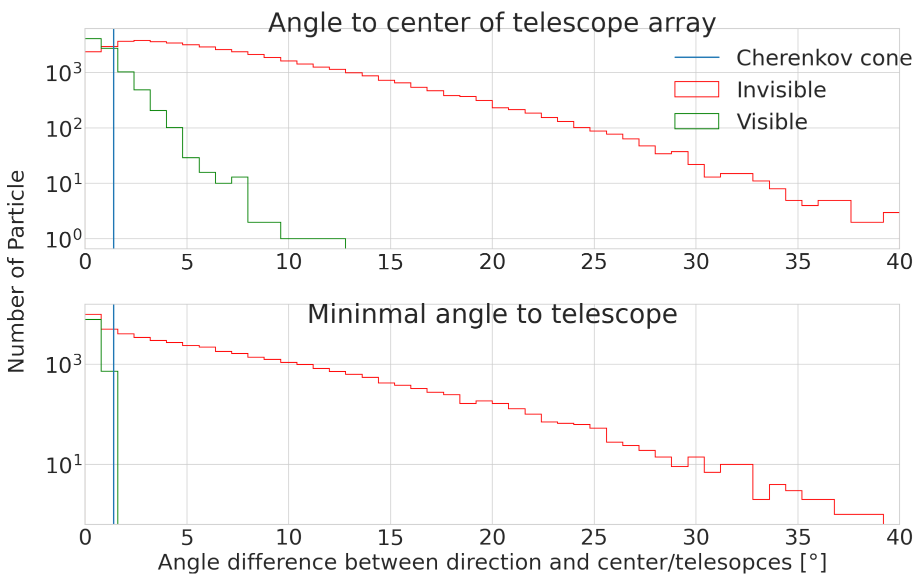

Figure 1: Displayed are two features of different computing complexity that allow the separating of tracks that, with a high probability, will not contribute to the observable Cherenkov photons. As basis for this analysis the preliminary locations and telescope sizes of the CTA North side were used.

Even though graphics co-processors are massively more powerful than CPUs, the efficient avoidance of unnecessary computations by suitable methods allows a significant reduction of runtime, despite the resulting overhead. The simplest applicable method for reducing the number of track segments passing the initial "Input Stage" (2.1) consists mainly of a single geometric cut. Depending on the energy of the shower and the expected amount of photons, one can choose, between a simple method that uses the angle between the flight direction and the vector to the center of the experiment, and a more computationally intensive method that uses the minimum angle between the flight direction and all experiment locations. In Figure 1 the preliminary positions of CTA North [8] were used for this purpose to demonstrate the worst-case effectiveness of the methods. For this worst-case study, a series of vertically incident was simulated using 1 TeV Gamma as initial particle. With cuts made at 12° or 5°, a reduction of ~14 % resp. ~32 % was achieved.

2.3 Photon Generation

The generation of photons can be divided into three parts:

- Calculating the number of photons
- Sampling of the emission point
- Calculating the direction of emission

Due to the different physical properties behind the emissions, two different kernels were developed.

2.3.1 Cherenkov Light

Calculating the number of photons emitted by each track is done with the Frank-Tamm formula , which leads to the following formalism:

$$N_{\text{cher}} = 2\pi\alpha z^2 L \frac{\lambda_1 - \lambda_2}{\lambda_1 \cdot \lambda_2} \cdot (1 - (n\beta)^{-2}), \tag{1}$$

with charge z, wavelength λ, refractive index n and track length L. Because of its small influence of much less than 1 ‰ on the amount of photons created, atmospheric light dispersion is neglected by averaging the wavelength-dependent refractive index over the interval of interest. If required dispersion can be added in the future with the accompanying loss in performance. To reduce the additional workload imposed by the artificial splitting of particle tracks used by the classic midpoint formalism, in which all photons are emitted from the track center, the default track length given by CORSIKA is maintained. To avoid imprecise handling and increase the simulation accuracy, the photon origin is sampled by an exponential distribution fitted to the local refractive index profile.

The photon emission direction is first generated in the vertical direction:

$$(\cos(\varphi_{\text{rand}})\sin(\theta_c), \sin(\varphi_{\text{rand}})\sin(\theta_c), -\cos(\theta_c))^{\intercal},$$

then rotated into the correct particle reference frame.

2.3.2 Fluorescence Light

Fluorescence emission can be calculated similarly to Cherenkov light in the previous section but with a light yield given by Kakimoto et al. [9]. One possible optimization is that not all photons have to be generated, but only those that point spatially in the direction of the experiment. This is done by reducing the solid angle to a small area and then sampling the random numbers from it.

2.4 Photon Propagation

A correct photon propagation through the atmosphere would involve a computing-intensive numerical integration along the path with changing refractive index. This scaled up for several million photons per shower would result in a slow down of several orders of magnitude even with GPUs. On the other hand, rectilinear propagation is very fast, but leads to errors that increase sharply with the zenith angle.

The combined approach allows a significant reduction of the physical inaccuracies without affecting the propagation time too much. For this purpose, an interpolation table is created before

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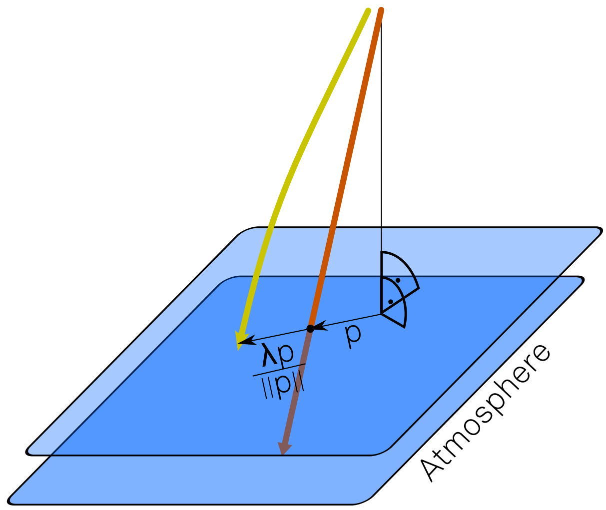

Figure 2: Displayed is the schematic structure of the planar Atmosphere with correction factor λ.

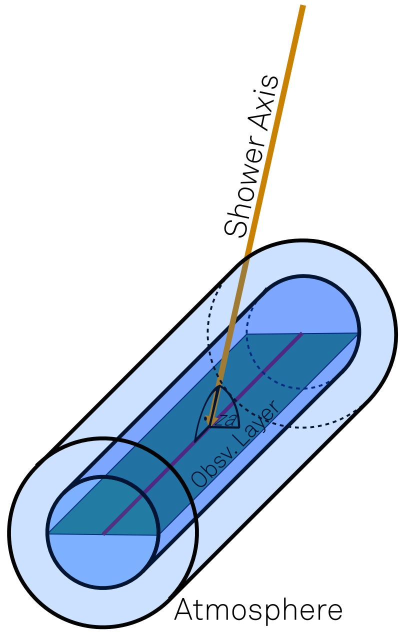

Figure 3: Shown is the schematic structure of the cylindrical atmospheric. Here the red main axis is a tangent to the earth's surface and orthogonal to the shower axis (orange).

the simulation, which contains a multiplicative correction factor. This can then be applied to the impact point of the photon to shift it accordingly. In addition, these corrections are also made with the time of arrival and the angle of impact. This procedure is already used in a similar form in CORSIKA 7.

The atmosphere description used as example here is the so-called "US standard atmosphere" [10] model. Depending on the required precision or run-time different simplification can be made. The simplest and fastest model is the assumption of planar atmosphere, i.e. without Earth curvature. This assumption allows to exploit symmetries that significantly reduce the required complexity to 2D and so the size of the tables. This table is as example displayed in Figure 4. It displays the scaling factor λ, which describes the shift along the normalized project vector on the ground plane as seen in Figure 2.

The use of specialized GPU hardware, the so-called texture unit, allows an extremely efficient interpolation between the individual values of the 2D table. This is done in parallel to the other computations, so that the method has almost the same runtime properties as the strictly linear propagation.

Even for this model the error drastically increases at very high zenith angles because the simplification as a plane atmosphere shows a strong deviation from the real-world behavior. However, a table generated for this purpose is considerably more extensive and, with 4 dimensions, no longer be interpretable in hardware. Further work shows promising results by removing one dimension and interpolating the atmosphere as a long cylinder (Figure 3) instead.

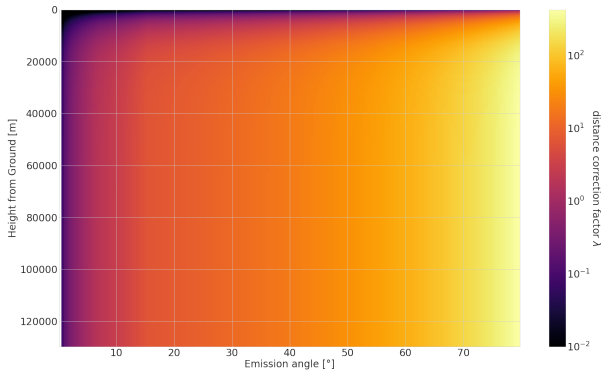

Figure 4: Correction factor for the straight line propagation based on a simplified planar atmosphere model.

2.4.1 Output

After propagation of the individual photons there is a last reduction step to reduce transfer time between GPU and CPU. This step removes all photons not hitting predefined areas. Those are usual telescope positions, but can be extended to encompass the whole shower. One sample is shown in Figure 5 displaying the unfiltered cascade, light emission on ground and the preliminary CTA Position projected on a 2D layer.

3. Summary and Outlook

The implementation of Cherenkov light for highly parallel hardware like GPUs shows promising results in terms of overall performance and flexibility. The statistical comparison between the classic photon generation and the GPU solution still needs to be extended and additional systematic studies with Cherenkov telescopes need to be performed.

After testing is complete the kernels will be moved out of the Python applications to the C++ framework to allow easier use and faster interconnect between CPU and GPU code.

Acknowledgments

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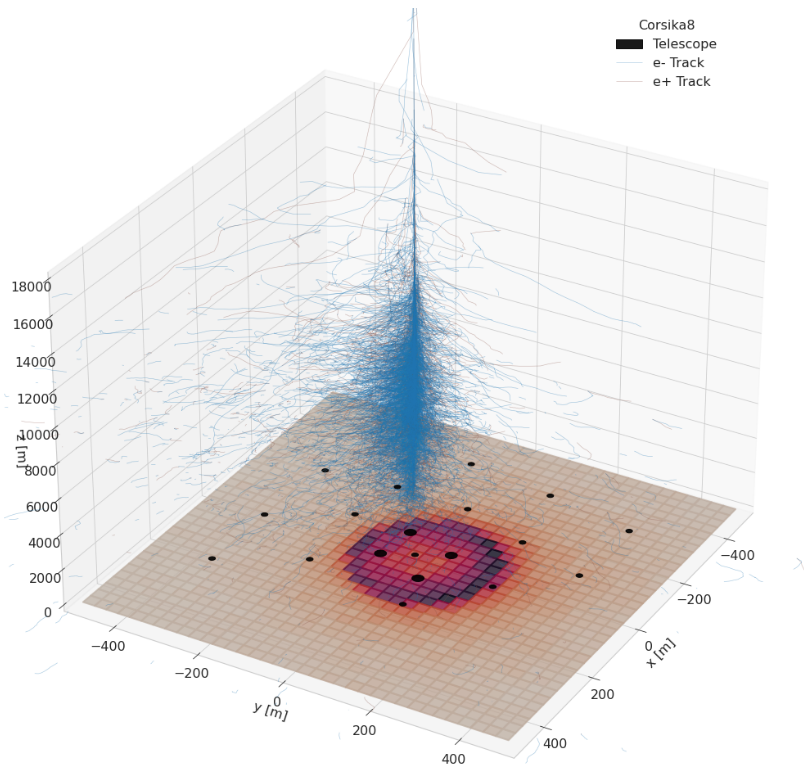

Figure 5: Displayed is a 1 TeV shower with its cherenkov light distribution on ground level.

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