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GPU based photon propagation for CORSIKA 8

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GPU based photon propagation for CORSIKA 8

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Abstract. Right on time for several large-scale experimental upgrades, the widely used and long-standing air shower simulation toolkit CORSIKA 7 will be updated to a "state of the art" C++ simulation framework. To meet the simultaneously rising demand for high-quality air shower simulations and the ecologic necessity to reduce energy consumption several new possibilities for optimizations will be tested.

One of the biggest runtime consumers in the classic simulation is the propagation of fluorescence and Cherenkov photons through the atmosphere. With the rising popularity of highly parallel computing architectures, the runtime of this specific workload can be reduced significantly. In this Work, the most common architecture, in the form of GPUs, is utilized for this task. Two competing implementations in Cuda and OpenCL are compared and different techniques presented that enable a high GPU utilization.

1. Introduction

With the advancements in precision and size of next-generation cosmic ray experiments the requirement on quality, precision, and amount of simulated data are rising rapidly. The simulation as the essential backbone of most detector studies and later data analysis can not be neglected and is required to improve accordingly. The well known and established CORSIKA 7 [1] simulation software does meet most of those requirements up till now. Over the course of more than 30 years of development of the Fortran77 code base, with several independent contributions, the software has become increasingly difficult to maintain and extend. This led to the decision to begin development of a state-of-the-art successor to meet current and future demands. This CORSIKA 8 Framework [2] enables the implementation of the here presented study. In the current status, CORSIKA 8 is in very active development and only some individual parts could be tested inside the simulation. The remaining results were generated in a testing environment which is used for controlled development.

Comparing the runtimes of the different modules in CORSIKA 7, it becomes clear that the simulation of Cherenkov light [3], radio emissions set aside, makes the largest contribution to runtimes overall (see figure 1). With the billions of photons generated, depending on the settings, 70% to 90% of the simulation time is invested there. Based on previous work of optimization of atmospheric cascade simulation presented in [4,5] and the recent hardware development (see Figure 2) the leading unexplored method for runtime reduction is the utilization of specialized high-performance hardware. In this case, the widely available Graphical Processing Unit (GPU) was chosen. With several thousand simple parallel executing cores it is the most suitable type of hardware for the mostly geometric propagation of individual photons.



Callees	CPU Time: Total	CPU Time: Self
▼ cerenk	2078.871s	533.937s
▶ distip	449.052s	203.941s
▶ tofip	336.495s	214.020s
▶ rmmard	231.852s	231.438s
▶ rhof	190.258s	20.957s
▶ __cos_avx	179.945s	38.086s
▶ __sin_avx	95.118s	25.432s
▶ telout_	55.212s	54.892s
▶ __tan_avx	2.140s	1.960s
▶ thick	1.880s	0.290s
▶ __jeee754_log_av	1.280s	1.280s

Figure 1. Profiling results of the Cherenkov routine from CORSIKA 7 for a 2 TeV Gamma-Shower with 2232 seconds runtime.

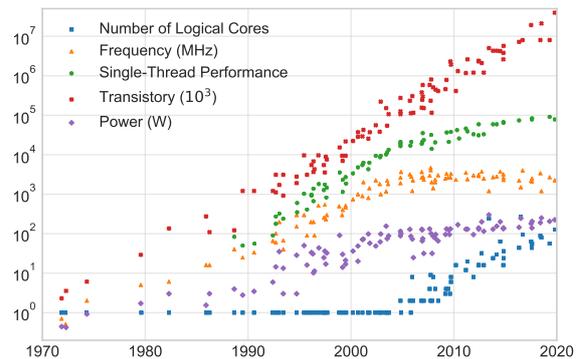


Figure 2. Displayed is the CPU development over the last 48 years. It is visible that recently the number of cores increases, while the performance per core stagnates [6].

2. Basic Architecture

With the schematic overview over the individual modules and control flow given in Figure 3 this section describes the individual steps of the simulation pipeline.

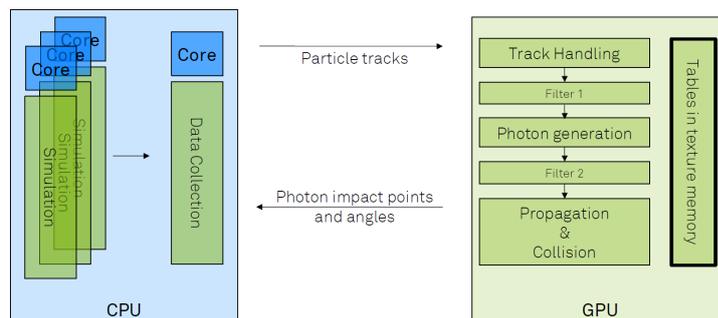


Figure 3. Schematic overview of the program structure. The accumulation of particles is necessary to reduce the impact of the overhead for data transfer between CPU and GPU. The two filter stages allow an early reduction of undetectable particles before more expensive operations are executed.

2.1. Data aggregation

To facilitate the most efficient usage of a wide variety of existing computing resources, it is mandatory to provide a flexible architecture with dynamic runtime optimizations. This is only possible if the CPU based core particle simulation is decoupled from the GPU light propagation algorithm. This makes it possible to use a server cluster with a single GPU on each node or variants with a combination of high-density nodes with several GPUs and interconnected nodes without GPU.

An additional advantage of this separation is the possibility of a data aggregation stage, which collects single tracks of several particle simulation instances and thus can transfer up to several thousand single tracks simultaneously to the GPU. An insufficient number of tracks transferred, resulting in a low number of photons, can lead to an underutilization of the GPU, which means that internal latencies can no longer be hidden.

2.2. Track Handling

This first input stage, running on the GPU, converts the particle format and removes Cherenkov light emitting tracks with $\beta = \frac{v}{c} = \frac{v}{nc_0} < 1$ (with a refractive index of n). Note that variations of the refractive index along the tracks may partially allow the emission of Cherenkov light. For

Table 1. Input data transferred to the GPU.

Quantity	Description
3	Start position
3	End position
1	Charge
1	Velocity

Table 2. Output data transferred from the GPU.

Quantity	Description
3	Position
2	Angle
1	Wavelength

a computationally efficient verification only the endpoints can be inspected. For track lengths in the range of several 100 m this leads to a negligible inaccuracy far below 1%.

2.3. Filter stages

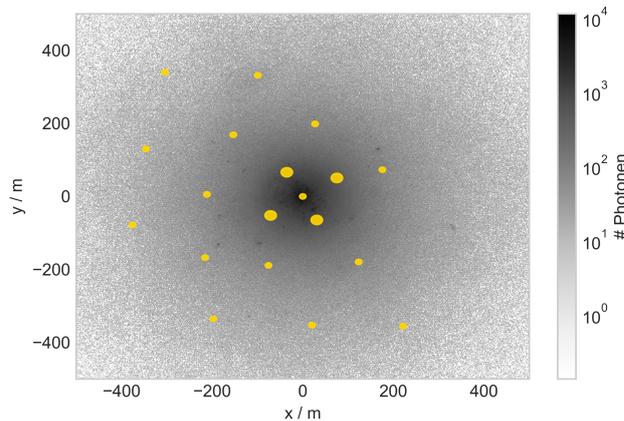


Figure 4. Ground distribution of Cherenkov light for a possible configuration of CTA North. It is visible that only a very small fraction of photons are detectable. With simple geometric cuts, the overall workload can be more than halved.

Due to the large geometric size of the atmospheric cascades compared to the instrumented area (see figure 4) only a small fraction of all possible Cherenkov photons can be measured. The early detection of measurable traces or single photons by several filter steps within the computational pipeline can significantly reduce the number of expensive computational steps. Currently implemented geometric cuts reduce the workload by up to 50%.

2.4. Photon generation

The photon generation is one of the most runtime intensive parts. To calculate the number of photons the Frank-Tamm formula [7] (equation (1)) needs to be integrated over each track.

$$\frac{d^2 N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2} \cdot \sin^2(\theta_c) \quad (1)$$

A simplification, which is applicable to real atmospheric conditions, is that the associated refractive index changes only gradually over several 100 m. Using the assumption of short trajectories, less than a few percent (depending on the required precision) variation of the initial and final refractive index, the refractive index can be treated as constant or linearly changing. This simplification enables the calculation of an average number of Cherenkov photons disregarding wavelength-dependent phenomena like dispersion. With the inclusion of constant hardware effect such as the acceptance of the sensors used, reflectivity and transmission the number of emitted photons can be drastically reduced (shown in figure 5).

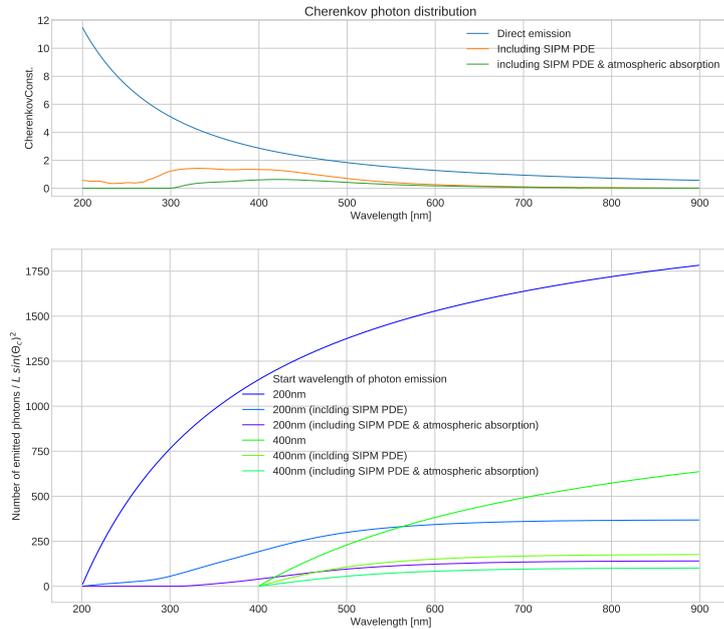


Figure 5. Shown are observable photon emission spectra with different absorption effects in the upper and the the resulting integrated photon flux in the lower plot. Both are divided by $L \sin^2(\theta_c)$, which is composed of the track length L and the Cherenkov cone angle θ_c . Considering the absorption probability of different processes, it is possible to reduce the number of photons to be processed significantly.

2.5. Propagation to observation plane

In first-order photon propagation through the atmosphere can be described as a linear process. With higher zenith angle and longer track length the deviation from a line through the change in refractive index along the track becomes more significant (see figures 6 to 8). With the

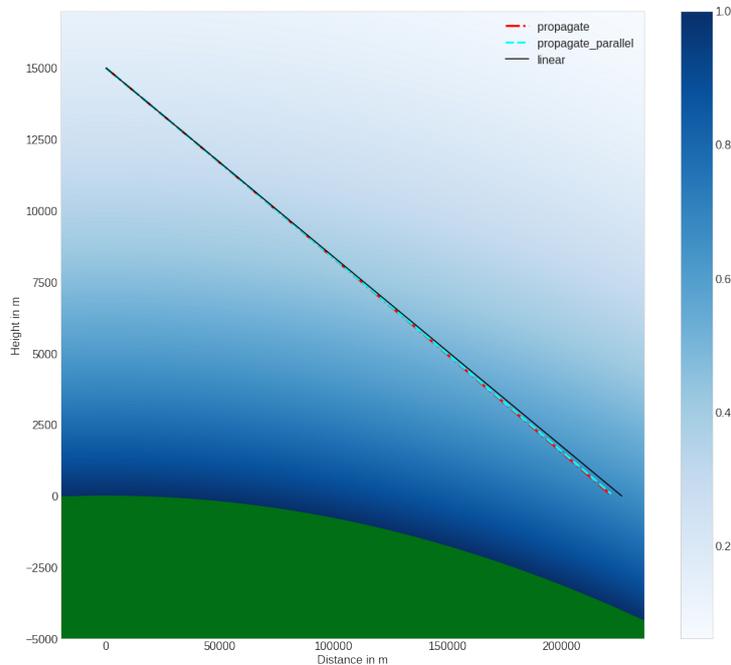


Figure 6. Displayed is the deviation of the straight line photon propagation compared to the physically correct method that takes into account for refractive index and curved atmosphere. In figure 7 and 8 the effect is displayed in more detail.

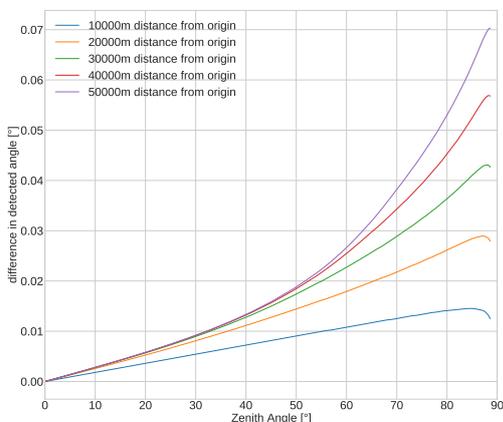


Figure 7. Displayed is the angle difference on the observation plane for the straight line propagation compared to the physically correct one with different initial distance to the detector. The difference is at the lower limit of currently observable resolution and should therefore be taken into account.

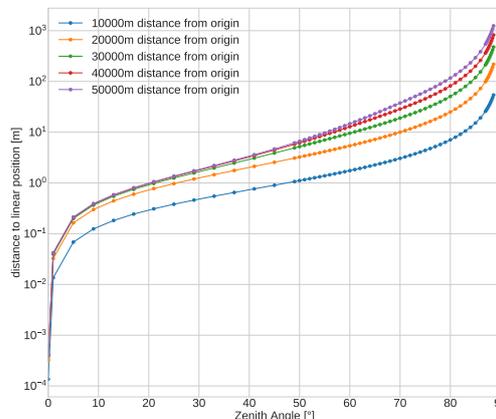


Figure 8. Displayed is the distance difference for straight line propagation and the physically correct propagation for photons with different initial distance to the detector.

constraint of a complex and often changing tabulated atmosphere the use of an analytic solution is impossible. The step by step processing by reduction to thin atmospheric layers (e.g. Snell's law) is feasible but runtime intensive. The faster but similar precise method used here is based on precalculated correction tables. Those three-dimensional tables can be stored inside the GPU texture memory which allows linear interpolation between values in hardware and fast access.

3. Conclusion and Outlook

The implemented methods show promising results for a faster and more precise simulation of the Cherenkov photons. With more than tenfold acceleration in early toy studies, which does not include all of the acceleration methods presented above, the total run time and power consumption can be drastically reduced. With higher utilization by a full scale simulation and use of the presented improved methods, the average run time should be reduced by another order of magnitude.

With the recently implemented electromagnetic interaction model PROPOSAL [8, 9] for CORSIKA 8, the implemented propagation method can now be tested in a real context for the first time.

If the photon data are already available on the GPU, additional steps like ray tracing of the optical hardware can be included with little impact on the overall simulation.

Acknowledgments

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